Geoinformatica (2007) 11:217–237
DOI 10.1007/s10707-006-0001-0

Contextualization of Geospatial Database Semantics for Human–GIS Interaction

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Received: 18 October 2005 / Revised: 7 April 2006 /
Accepted: 2 May 2006 / Published online: 20 January 2007

Abstract Human interactions with geographical information are contextualized by problem-solving activities which endow meaning to geospatial data and processing. However, existing spatial data models have not taken this aspect of semantics into account. This paper extends spatial data semantics to include not only the contents and schemas, but also the contexts of their use. We specify such a semantic model in terms of three related components: activity-centric context representation, contextualized ontology space, and context mediated semantic exchange. Contextualization of spatial data semantics allows the same underlying data to take multiple semantic forms, and disambiguate spatial concepts based on localized contexts. We demonstrate how such a semantic model supports contextualized interpretation of vague spatial concepts during human–GIS interactions. We employ conversational dialogue as the mechanism to perform collaborative diagnosis of context and to coordinate sharing of meaning across agents and data sources.

Keywords GIS · context · semantics · ontology · human–computer interaction

1 Introduction

Geospatial data semantics deal with representations of geographical world as interpreted by human users or communities of practitioners. Representation and reasoning on the meaning of geospatial data are critical for the development of interoperable geospatial data and software [6], [35], geographical information retrieval [36], and automated spatial reasoning [13]. Recent progress on the semantic geospatial web [15], [43] highlights the need to make spatial data semantics explicit and available to search engines. However, it is extremely difficult to capture and maintain semantic knowledge of geographical data because of the complexities of geographical categories [64], geospatial languages [24], and heterogeneous,

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multimodal, and multimedia representations of spatial data. At the moment, geographical information systems either impose simple semantic structure a priori or do not address the issue of semantics at all, leaving the burden of meaning construction to the user. Such solutions (or lack thereof) are extremely inadequate in the current stage of geographical information technologies where massive exchange of geospatial data from heterogeneous sources must be supported.

The search for solutions to interoperability of spatial data sources and application domains has been marred with a variety of semantic difficulties that are unique in the geographical information domain. Within geographical information science, ontology has been used to define a common vocabulary that minimizes the semantic problems in interoperability, metadata modeling, communicating meaning of data across domains, and data integration [9], [19], [36]. Ontology provides a method for identifying categories, concepts, relations, and rules that prescribe theories of the geospatial domain [47], [64]. Despite the increasing enthusiasm and popularity of the topic (as evidenced by multiple workshops and journal special issues in recent years), there has also been general dissatisfaction on the lack of progress in dealing with the complexity of geo-spatial semantics. As indicated in a recent survey on the ontological issues in GIScience [2], there has been no comprehensive ontology for geo-spatial domain, and no definitive methods for ontology derivation available to the geographic community. The uses of the term ‘ontology’ in literature are often found to be confusing, and some scientists have even put a degree of doubt on whether ontology truly provides a new paradigm for semantics in the geographical domain [75].

Why do ontological approaches, which are so widely accepted in other domains (like business information systems), fail to generate the expected solutions in geographical domain? There is no doubt that shared ontological commitment facilitates the communication of meaning and knowledge. However, there are also limitations of such methods that have not been made explicit in the GIScience community. Ontology-based approaches are accepted as the panacea for all sorts of geospatial semantic problems without having been questioned the validity of their general assumptions when applied to the geographical domain. As to be explained in the next section, the geographical domain does not meet the set of criteria (as specified by Gruber [29]) necessary to have a good design of ontology as a unified theory of geospatial semantics. In particular, the geospatial domain is highly unstructured and lacks consensual agreement on the basic sets of concepts, categories, and entities. The peculiarities of the geographic domain were well stated previously by Smith and Mark [63]. According to them, the problems associated with defining a comprehensive foundational ontology of GIScience lie in the inherent vagueness and context-dependent nature of geographical categories, geographical representations, and geographical interpretation. Geographical objects are tied intrinsically to their spatial and temporal context; representations of geographical locations, regions and boundaries are dependent on the context of use; classification of objects into geographical categories is scale-dependent and size-dependent; and interpretation of spatial concepts is dependent on human cognition. There exist many different representations of the same geographic reality, each tailored to meet the need of a particular type of use, data quality requirements, and efficacy of operations [33]. As demonstrated by Egenhofer [15], there are a large number of ways that ‘lake’ can be defined, characterized, and demarcated, all of which are valid within proper contexts. Understanding the meaning of “lake” requires intimate knowledge about the context within which ‘lake’ was mentioned, as well as how the word ‘lake’ takes on meanings in that context. Ontology approaches do not work well with a domain of such nature. It is a contestation of this paper that a theory of geospatial data semantics cannot be solely based on ontology because it is neither practical nor theoretically possible to develop and maintain a clearly defined and coherent ontology for the domain of geographical information science. There is a need for the development of new methods for capturing spatial data semantics, which should be based on a deep understanding of the nature of the geographic domain.

To address the limitations of ontology-based approaches in modeling geospatial data semantics, this paper proposes a context-driven and context-mediated semantic model of geospatial information. It extends ontology-based methods with an explicit model of contexts. The notion of context here covers broadly the characteristics of typical applications and scenarios of use, and serves as an additional conceptual modeling mechanism that complements the traditional ontology-based abstraction and modeling methods [68]. This model supports the reasoning of spatial data meaning through coupling a context-driven data model with a context-mediated mechanism for semantic interchange. At the conceptual modeling level, we represent semantic knowledge of a geospatial database using a contextualized geo-ontology (C-GeoOWL), following the work of Bouquet et al. [7], [8] on contextualized ontology. A contextualized geo-ontology is a context-ontology package (or an ontology wrapped by a context) that represents an unambiguous and coherent theory about a portion of geographical reality within a prescribed context. Since contexts can be specified at many levels, ranging from general to specialized, multiple ontologies can co-exist in a system and jointly describe the semantics of one or more data sources. At run-time when data are shared or communicated, contexts are used as the first-class objects that mediate the ontology alignment and semantic conflict resolution. This is accomplished through an intelligent agent that explicitly captures knowledge about defining features of and proper behaviors within a context in the form of contextual schemas (C-schemas) [72]. We believe that the combination of contextualized geo-ontologies and C-schema-based semantic reasoning provides a complete solution to geospatial semantics, and has the potential to be generalized to other domains of a similar nature.

The work reported here is an outgrowth of a larger research project, called DAVE_G (Dialogue-Assisted Visual Environment for GeoInformation) [11], [45], [61]. During this NSF-funded project, we made initial success in integrating multimodal technologies, conversational dialogues, and large-screen geovisualization technologies for the purpose of supporting individual or group work with geoinformation for time-critical applications (such as crisis response). Computer vision and speech processing techniques are used as a means of interpreting information requests made through spoken language and free-hand gestures. Compared with traditional desktop GIS, DAVE_G requires less prior training and less conscious attention while achieving fast access to a large volume of geospatial data.

DAVE_G represents one step further towards the type of ease-to-use interfaces envisioned by Mark and Gould [46], but it is still far from being as natural as requesting information from a human GIS expert. Besides the issues of imperfect speech and gesture recognition, a main challenge for enabling multimodal interactions with multi-layered maps is the difficulty in interpreting the (context-sensitive) meaning of the information request from human and match it with the data known to the system. If we consider both human and GIS as cognitive systems, their representation and communication of spatial concepts are fundamentally different. Human uses of spoken language and gestures are highly flexible, contextualized, and full of vagueness and ambiguities, while computers only understand languages with well-defined grammar and semantics. Using shared ontology approaches to bridge the semantic gulf between a human and a computer seems impossible, because they do not have much in common in the ontology level. However, meaningful communications can still happen when a human and a GIS are engaged in a concrete and shared activity context. This idea was initially applied to the problem of vagueness in spatial concepts [10], but there was no formal specification of contexts in that work. This paper is the first time that contexts are elevated into the top semantic modeling and semantic mediation mechanisms for human–GIS interaction.

2 Background and related work

This section provides a brief review of the notions of semantics, ontologies, and contexts, which are central to the ideas presented subsequently. It also highlights our interpretation of significant works that have informed our methodology development.

2.1 Spatial data semantics

Semantics of data is a form of agreement among agents regarding a conceptualization of the real world while interacting with an application or domain [49], and hence is the basis for an interpreting agent to derive meaning from the data. Spatial data semantics can be understood by tracing back to the process of how spatial data were created. Spatial phenomena may be perceived and conceptualized from diverse viewpoints and concerns that often result in idiosyncratic treatments of space. The creation of spatial data is commonly the result of a complex process [40] involving (1) defining and selecting the aspects of the world to be modeled, (2) specifying important entities as well as the necessary and sufficient properties for identifying the entities (such as a 'wetland'); (3) recognizing the existence of instances of such entities; and (4) demarcating the entity instances on the ground. Interpreting data semantics is the reverse engineering of the above spatial data creation process to identify the mapping between a representation and the reality represented. Every representation is necessarily an approximation of the geographical reality, and the degree of generalization, simplification, accuracy, and completeness of the data is designed to fit the specific use, with no guarantee of broad applicability.

To facilitate the exchange of data at the semantic level, various approaches to capture spatial data semantics have been developed. These approaches form three groups: *metadata* modeling, integrity constraints and consistency rules of *data models*, and conceptual modeling using *geographical ontology*. Metadata standards, such as the Federal Geographic Data Committee (FGDC), National Spatial Data Infrastructure (NSDI), and GeoSpatial One-Stop, attempt to describe syntactic and schematic knowledge about data sources for the ease of data sharing and access. However, these standards have serious shortcomings when dealing with qualitative, spatial or temporal information, which is often incomplete or imprecise [3]. Geographical metadata are provided mainly for consumption by humans, who judge its fitness of use. Alternatively, spatial data models have been extended with geometric entity classes, topological relationships, and geospatial constraints to capture the parts of semantic information associated with geographical data. Major versions include Geographic Entity-Relationship Model (Geo-ER) [32], GeoSpatialTemporal Unified Semantic Model (ST-USM) [38], concept-based OOGIS model [42], and GMOD model [14]. These models, although semantically rich, are rarely captured together with the data; instead, semantics become implicit in the resulting database schema, which is not directly consumable by computers and other semantic agents.

Pure syntactic approaches to spatial data semantics, such as metadata and data models (discussed above), are the easiest to implement, but they are heavily reliant on the existence of commonly accepted standards (such as standards for specifying geospatial metadata and standards on database schemas). *Standardization* is currently being promoted by the Open Geospatial Consortium [54]. However, it is extremely difficult and often impossible to impose standards because of a lack of agreement on formalized meanings. More importantly, standardization destroys the design autonomy (the ability to choose data models, naming, and implementation details) among interacting systems, which is not favored in the current distributed information environment.

In order to enable semantic interoperability while maintaining autonomy, recent research has moved away from a focus on data sharing to a focus on knowledge sharing. The idea is to support high-level, context-sensitive information requests over heterogeneous information sources while hiding system, syntax, and structural heterogeneity [62]. Foundational research regarding this direction has been focused on the notions of ontologies and contexts.

2.2 Ontologies of geographical information

Ontologies specify formal, agreed-to logical theories for an application domain [30]. These logical theories consist of domain rules and statements that are true according to a certain conceptualization that is shared and agreed upon by all applications in a domain. Geo-Ontology takes geography as one application domain, and attempts to create a set of concepts about space fully agreed upon by all applications in the geographical domain. Ontologies have played an essential role in many areas of geographical information science, such as the integration of geospatial information sources [19], [62], the specification of consistency and data quality rules [22], [58], GIS interoperability [9], [27], geographical information retrieval [36], [73], and modeling user activities [39]. Recently, the University Consortium for Geographical Information Science (UCGIS) recognized the Semantic Geospatial Web [15] as a key research theme [21]. The development of ontologies for geographical information has followed two distinct approaches:

(1) *Philosophical approaches* for the identification of top-level categories of geographic domains, taking reality as objective existence independent from any particular views or applications. Top-level ontologies are commonly organized into hierarchical concepts. Concepts specific to top-level geo-ontologies include ‘ontology of boundaries’ [65], ‘ontology of geographic fields,’ ‘image schemata’ [25], and ‘common-sense geographical categories’ [64].

(2) *Knowledge engineering approaches* that aim at the specification of application-specific, purpose-driven ontologies supporting information system development. Application specific approaches to ontologies do not assume an absolute independent reality, but focus on defining the categories and relations within a specific area of application [59]. Kuhn [39] argued that ontologies for geographical information should be designed with a focus on human activities in geographical space. He believes that an ontology unrelated to human activities makes no sense. Similar views are also expressed in Camara et al. *action-driven ontologies* [12], and Timpf’s work on *ontologies of wayfinding* [69]. This line of research is still in the early stage of development, and more issues on elicitation and implementation are to be addressed.

It seems that GIScience needs all these different ontologies and approaches, but there are constant tension between the need to form a unified ontological theory of the geographic domain and the specific needs of subdomains and applications. Any interesting collection of geographical data is likely to include data with varying degrees of general and application-dependent meanings. Thus, multiple ontologies are likely to co-exist in one system. Without proper methods to constrain the scopes of these ontologies, the coherence of the data semantics is going to be destroyed. This will be a significant problem to be addressed partially in this paper.

Ontologies serve as a semantic bridge between data in the system and the reality in the world, but they do not automatically guarantee interoperability. We also need a conflict resolution mechanism to resolve potential differences in their ontological commitments when two agents (or two data sources) communicate. Promising approaches exist, including the Context Interchange Network (COIN) [26], Conflict Resolution Environment for Autonomous Mediation (CREAM) [56], and SemPro [37]. These systems, which generally follow the mediator-based approach [74], commonly require that all participating parties agree on the meaning of concepts a priori (i.e., shared ontologies). It is a prerequisite that the designers of a shared ontology be able to anticipate all the possible contexts of data use and correspondence at design time. Such stringent conditions cannot be created in openly distributed and dynamic environments, such as the semantic Web. Recent debate on various approaches for semantic interoperability [55] has made it clear that ontologies lack the flexibility and modeling power for ever-evolving semantic Web. The dictionary-like or model-theoretic definitions of semantics of concepts in an ontology fail to capture the tacit, experience-based, and context-adaptive nature of concept interpretation. With the emergence of grid computing, peer-to-peer computing [34], and ubiquitous location-based applications, ontology-based semantic web technologies are seriously challenged by their limited flexibility, scalability, and semantic granularity [1].

2.3 Contexts

There has been increasing recognition that contexts are important issues in semantic interoperability. Sheth [62] proposed to incorporate the context of an information object as the primary vehicle to capture the real-world semantics of the object. Context has influence on all stages of semantic processing. At the conception level, context drives how phenomena are perceived and abstracted, resulting in different object categories, properties, geometries, and relationships. At the representation level, context influences the choice of data models, the scale of geographical representation, geometric and thematic details in order to maximize the economy of representation and efficiency of access. In the stage of communication and interaction, understanding the context of an information request can help the system to quickly focus on the portion of the database relevant to the current query. The relevance of contexts to semantics was also confirmed by the work of Barsalou [4], [5] who, through psychological experiments, showed evidences for the existence of context-independent properties and context-dependent properties in human concepts. This suggested that humans use semantic memory models that are neither totally generic nor totally contextual.

Frank [22] proposed a tiered framework of ontology development where context was a main component of the social ontology tier. His ontology of a reality is organized into five tiers: (1) the *physical tier* includes the basic concepts of space and time and laws of mass; (2) the *observation tier* includes concepts of samples, measurement scale, precisions, and various sensing methods; (3) the *cognitive tier* includes concepts of objects and their salient attributes recognized by humans while interacting with the world; (4) the *social tier* models concepts and terms that are socially constructed and context-dependent; and (5) the *knowledge tier* deals with concepts describing human mental states such as belief, judgment, and attitude.

To some extent, Frank's 5-tier ontology framework coincides with the DOGMA ontological framework [66] where contexts are used to circumscribe different representations of the same reality. DOGMA decomposes ontology into an *ontological base* and a layer of *ontological commitments*. The ontology base may contain many different conceptualizations about the same real world, organized as *contexts*. Each context has a unique context identifier and a group of conceptual relations, called *lexons*, representing domain facts specific to that *context*. Within each context γ, a term is uniquely mapped to one concept. The layer of *commitments* mediates between the ontology base and applications. Each commitment consists of rules that specify which lexons from the ontology base are visible for usage in the commitment. An ontological commitment can be regarded as a conceptual model of a particular application or a group of applications. The DOGMA framework is unique in the sense that it treats contexts as explicit components in ontology. Unfortunately, the DOGMA framework, in its current version, gives only a very simplistic account of contexts where each context is described by nothing but an identifier.

Furthering the trend of integrating ontology and context, Bouquet et al. [8] model the Semantic Web using contextual ontology (C-OWL). They believe that ontologies and contexts both have some advantages and, therefore, they should be integrated in the representational infrastructure of data semantics. A theory of data semantics must include multiple ontologies as local theories scoped by contexts. Concepts and terms within a contextual ontology are intended to be shared by all parties within the subdomain defined by the context. Terms containing information that is mutually inconsistent should be put into different ontologies separated by proper contexts. Sharing knowledge among different local ontologies is achieved via explicit mappings.

The three models (or frameworks) reviewed above have all taken contexts into account for structuring ontology base. However, none of them has developed any mechanisms for ‘hand-shaking’ between two ontology bases. The DOGMA framework pre-supposes the existence of at least one common ontological commitment between communicating agents, which needs to be set a priori. Our work inherits the idea of contextualizing ontologies, but extends beyond the existing work in two ways. First, we expand the notion of contexts to refer to any recurring patterns of information exchange activities, which can be subdomains, tasks, situations, or experiences. Second, we define a schema-based representation of contexts that allows rich characterization of contexts. The result is a new semantic interoperability framework based on context-mediated semantic hand-shaking.

3 Context-mediated semantics interoperability for geospatial information (CMSI-G)

In order to extend the existing ontology-based approaches for handling the context-dependent nature of geospatial semantics, we propose a framework for semantic interoperability of geospatial information, which is called *Context-Mediated Semantics Interoperability for Geospatial Information* (CMSI-G). As we have discussed in the introduction, the lack of agreement on the meaning of geographical concepts across multiple data sources is likely to cause semantic heterogeneity problem at the ontology level. The idea behind our approach can be generally described as follow:

(1) Contexts should be explicitly represented; contextual knowledge should be associated with context representations; and contextual knowledge should guide all facets of an agent’s behavior [72].

(2) A theory of geospatial data semantics should include multiple ontologies ranging from top-level generic ontology to application specific ontologies. Each ontology be associated with a context that ‘wraps’ around it. Semantics of an ontology is local to its

context. Ontologies are related through the generalization/specialization relationship of their contexts, as well as through explicit ‘lifting’ rules.

(3) With contextualization of data semantics, it is no longer required for two communicating agents (or data sources) to have common ontological commitment. Instead, we rely on context alignment and shared contextual knowledge to constrain semantic interpretation.

(4) Contextualization hides the heterogeneity of data at the ontology level, just like ontologies effectively hide the heterogeneity of data at the syntax level.

(5) Contexts and ontologies are two semantic coordination mechanisms for interoperability, with contexts taking priority over ontologies. In other words, commonality in contexts can over-ride heterogeneity in ontologies, but not vice versa.

The main body of our approach is the integration and extension of the work on *contextual ontology* (C-OWL) by Bouquet et al. [8] and the work on *context schema* (C-schema) by Turner [71]. The goal of this section is to describe various components of the CMSI-G framework and their interrelationships.

3.1 The CMSI-G framework

A CMSI-G framework consists of the following six components:

$\widehat{C}$ A context space which is a set of contexts $\{C_i \mid i=1,.., M\}$, where N is the total number of contexts

$\widehat{O}$ An ontology space which is a family of ontologies $\{O_i \mid i=1,.., N\}$

$\widehat{\Phi}$ A set of inter-ontology bridging rules $\{\Phi_{i,j} \mid (i, j \in \{1,.., N\})$ and $(i \neq j)\}$. Each $\Phi_{i,j}$ is a set of rules that specify how elements of ontology O_i relates to elements in ontology O_j, if any relationship exists

$\widehat{\Psi}$ A set of inter-context bridging rules $\{\Psi_{i,j} \mid (i, j \in \{1,.., M\})$ and $(i \neq j)\}$ that specify how context C_i relates to context C_j, if any relationship exists

$\widehat{\Theta}$ A set of rules governing context coordination

$\widehat{\Omega}$ A set of rules governing ontology coordination

Each of these components is again a complicated structure that is to be explained in more detail in subsequent sections.

3.2 A motivating problem scenario

In order to anchor the subsequent discussion in a concrete setting, we describe a simple scenario that highlights the need for contextualization of spatial data semantics. Suppose a person approaches a computer and asks for a map to be displayed by saying:

S*how me a map near SC town*.

The computer is expected to understand this request and compile a map that matches with the user’s conception of ‘near.’ In order to process this request, the system has to understand a number of concepts. First, it has to understand that ‘SC town’ is a geographical entity with geographical location, the extent of its area, its boundary (although can be vaguely defined), and numerous other characteristics. Second, the system must be able to intrepret what the person means by ‘near.’ ‘Near’ is a basic spatial concept that should be part of the ontology of geographical space. However, 'near' does not correspond to any fixed set of geographical entities. The part of the earth's surface that qualifies as "near SC town" depends on the actual context of the map request. Is this in the context of grocery shopping, or planning a vacation, or locating a new business office? If this is about grocery shopping, are we talking about driving a car, riding a bike, or walking? Figure 1 illustrates the idea that a person may well have two different senses of near ("Near 1" and "Near 2") for two different travel modes (drive or walk) in grocery shopping.

The above scenario presents a case of semantic interoperability between a human and a computer. Humans and computers rely on fundamentally different architectures for cognitive activities, and they maintain quite different ontological commitments regarding geographical space. Human conceptualizations of space follow a 'cognitive' view of the space, while computers (as formal systems) adhere to a 'scientific' view of space [16]. The scientific view, which is the basis for GIS representation of space, treats geographical space as a seamless and uniform space where a set of spatial concepts applies to all scales and all phenomena. In contrast, human cognitive categories and concepts about space come from experiences of interacting with the world through a variety of tasks and activities. Such knowledge can only be acquired piece by piece since geographical space is too large to be experienced all together. People view the same spatial situation quite differently depending on personal histories, the actual physical settings, and purpose. Humans' spatial knowledge is incomplete, biased, vague, and sometimes inconsistent. A data object has no unique and correct meaning; instead, semantics are interpreter-dependent and context-bounded. The communication of spatial concepts is considered successful when the receiver's evoked concepts are sufficiently isomorphic to the source's concepts [9]. Unfortunately, the differences in the way humans and computers derive meaning on spatial concepts present great challenges.

We have applied the CMSI-G framework in an extension of DAVE_G system to develop a systematic approach for communicating vague spatial concepts (such as *near*) in a multimodal GIS. Previous implementation of DAVE_G included a computational agent, *GeoDialogue*, as its dialogue manager which only carries one set of semantic interpretation rules

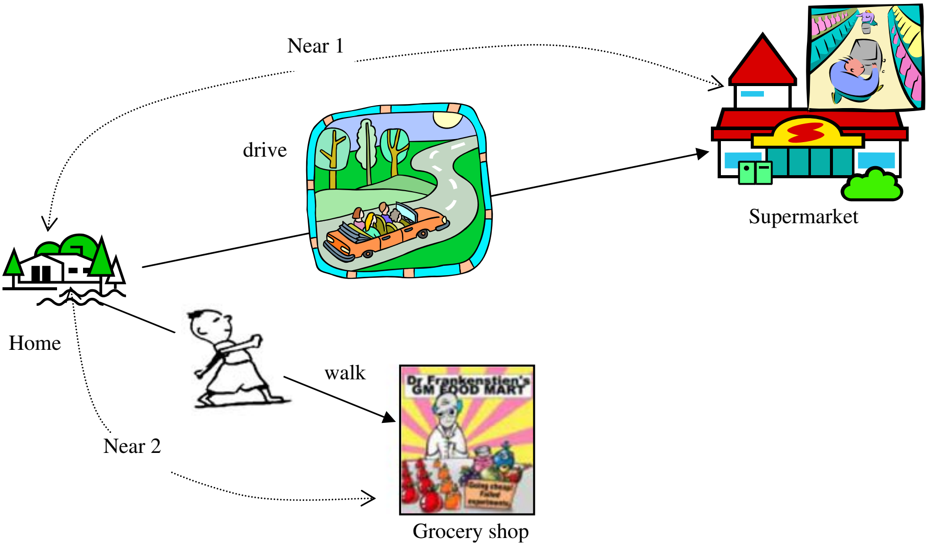


Fig. 1 The concept of 'near' in different contexts of grocery shopping

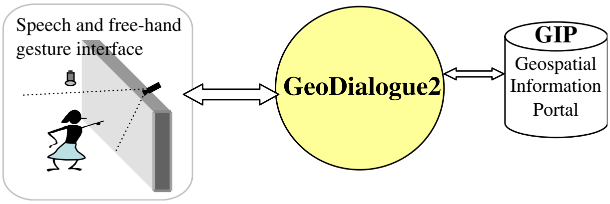


Fig. 2 GeoDialogue as a mediator of human–GIS conversation

(vocabulary and grammar) that are universally true. The newer version of this dialogue manager (we will called it *GeoDialogue2* thereafter for distinction) assumes a new role of being an intelligent semantic mediator (see Fig. 2).

In the subsequent sections, we will detail the different components of our CMSI-G framework (as introduced in Section 3.1), and demonstrate how GeoDialogue2 works in the grocery shopping scenario

3.3 Context space: $\widehat{C}$

The context space is defined by all the contexts known to an agent (be it human or computer). This section answers the following questions: what is a context? How contexts are described and represented? How are contexts related?

We rely on Turner's [71] definition of 'context':

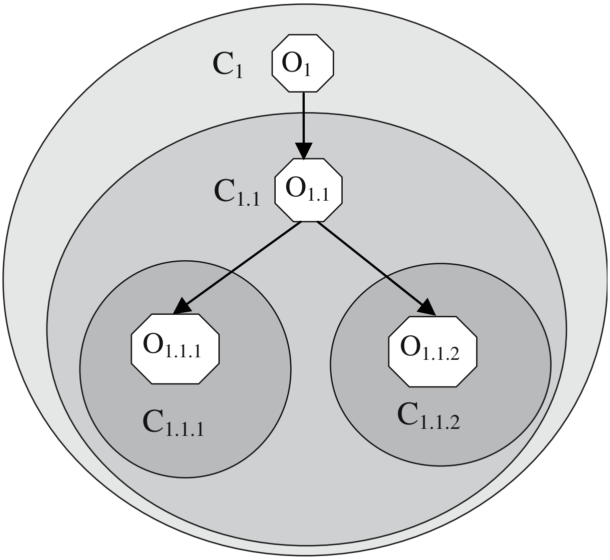
> A context is any identifiable configuration of the environment, and agent-related features that has predicative power for behavior.

Based on this definition, we distinguish the notion of contexts from the notions of situations. A *situation* is concerned with a concrete instance of an action (or interaction) that constitutes the basic unit of human experience. A situation is defined as all the features of the environment (both physical and social) surrounding an action (such as requesting a map). Although there are a large number of configurations of all the features that are present in a situation, there are only a small number of configurations of a subset of features that has predictive power on agent's behavior across situations. A context is a conceptual schema that subsumes a large number of situations that vary from one another along features that have no (or negligible) impact on an agent's behavior. Applications and domains can be considered as special cases of contexts. For example, within the domain of geographical information science, there are a number of application areas; within an application area (such as travel), there are many different contexts (by car, by bike; vacation, going to work, shopping, etc.).

Contexts vary in scope, from very broad to very specific, with broader contexts often containing more refined and specific contexts. An application domain may have collections of nested contexts. Figure 3 shows a possible structure of context space for the scenario described in Section 3.2.

A specialized context can be derived from a more general context by including more assumptions. If c is a context and p is a proposition, then c'=assuming (p, c) is a new context [48]. For example, 'shopping' can be a generic context where many features (what to shop, where to go, how to travel, etc.) of the context have to be explicitly described. A specialized context may be 'shopping for a textbook on a university campus' where we can normally assume that there is a bookstore on campus and that the dominant method of travel is by walking. A set of contexts with nested relations can also be used to capture

Fig. 3 Nested context space



C_1/O_1: Shopping
$C_{1.1}/O_{1.1}$: Grocery shopping
$C_{1.1.1}/O_{1.1.1}$: Grocery shopping by car
$C_{1.1.2}/O_{1.1.2}$: Grocery shopping by walking

different degrees of approximation to the modeled world, or different levels of ambiguity/generality in the meaning of concepts and statements. More details on approximation contexts and ambiguity contexts can be found in [31].

The content of a context is described by a context schema (or C-schema), per the work of Turner [71], [72]. A C-schema is a frame-like knowledge structure with a unique context identifier and contains both *descriptive* and *prescriptive* knowledge about the context it represents. Descriptive knowledge about contexts helps the agent to diagnose what context an agent is in when it encounters a new situation and allows the agent to bring all the knowledge it knows about the context to the understanding of the current situation. Relevant knowledge in this part of a C-schema may include:

- *Features of a situation that must present (or not present) in order to be considered an instance of this context.* Features of a situation that are expected if the situation is an instance of this context;
- *Context-specific ontology/meaning of particular concepts.*

Prescriptive knowledge informs an agent how to behave appropriately in a context. It consists of:

- *Knowledge about what goals should be focused on in the context.* When multiple goals compete for limited human attention and cognitive resources, an agent uses contextual knowledge to weigh relative importance of these goals, and allocate attention and resources accordingly.
- *Knowledge about selecting actions to achieve goals appropriately in the situation.* Choosing a means to achieve a goal is highly context-dependent. For example, a person

who is hungry may choose to pick some fast food from across the street if during weekdays, but he/she may choose to drive a few miles to dine in a favorite restaurant because it is a weekend. An agent's contextual knowledge allows the agent to form a plan of actions relatively effortlessly.

- *Knowledge about how to interpret new events*. If an event is detected, is it expected (or unexpected) in the current context? Is this event important to the current context? How an event is to be handled appropriately?

We now come back to the problem scenario of Section 3.2 and provide an analysis of context space for communicating spatial concept 'near.' A general sense of 'near' can be understood as how much further from a central location that an agent is willing to travel in order to perform certain activity. Exact meaning of 'near' depends on such factors as the geographical region/place [18], [60], [77], the task [17], and personal characteristics (such as the ability to navigate and the tolerance of travel time, etc.). Without knowing such contextual information, a request "Show me a map near SC town" is ambiguous to an agent (in this case, *GeoDialogue2*). Suppose that *GeoDialogue2* has had many experiences of communicating the concept of 'near' with humans in a variety of situations, and it has formed a number of contexts in which *GeoDialogue2* knows how to interpret the concept of 'near.' In order to create an initial set of contexts to bootstrap *GeoDialogue2* implementation, we conducted a set of user interviews for eliciting knowledge about context-specific meanings of 'near.' In each interview, a paper map of a local city and its surrounding area is presented to the candidate who was asked to draw the area he/she believe to be near. The results of this experiment provide the baseline knowledge for compiling a set of context schemas. An example of a context schema is shown in Table 1. This context models the typical situation of driving to grocery store in a small town. Within this context, the linguistic variable 'near' has a context-specific fuzzy member function for estimating the geographical coverage. This schema contains the C-schema features necessary for disambiguating the meaning of 'near' using context assessment.

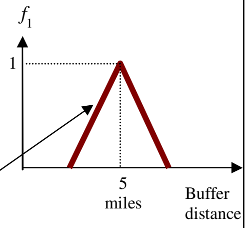
Contextual knowledge about grocery shopping includes the typical procedures of shopping groceries, geospatial settings, transportation methods, frequency, etc. In the problem scenario, both the interpretation of spatial concepts ('SC town' and 'near') and the map generation behavior depend on the recognition of the proper context and the knowledge about the local ontology within that context.

3.4 Ontology space $\widehat{O}$

We model the semantic space of a geographic domain using a coordinated set of ontologies. These ontologies are formed through partitioning an information base or a knowledge base into possibly overlapping chunks, and using contexts (as defined in Section 3.3) as abstraction mechanisms (following the work of [52], [68]). Each ontology serves as a local theory of data semantics, and is coherent and valid within the scope of the associated context. In this sense, ontologies are implicitly related through the relationships of their associated contexts. As an example, $O_{1.1}$ and $O_{1.1.2}$ in Fig. 3 are related through contexts $C_{1.1}$ and $C_{1.1.2}$. An ontology is a structured set of objects (classes, class instances, subclasses, superclasses, etc.), in which each object is associated with a set of names and (possibly) a reference. Within an ontology, objects can be related through a set of structural relationships, such as attribution (ATTR links), classification (IN links), and generalization (ISA links) [51]. Following an object-oriented approach, we allow ontology inheritance from a more general context to a more specific context, thus avoiding duplications.

Table 1 Context schema for $C_{1.1.1}$

(1) Context ID: *104*
(2) Defining features of context
  (2a) Task (such as shopping, vacation): *shopping*
  (2b) Geographical area: *State College, Pennsylvania*
  (2c) Transportation tools: *driving*
(3) Expected features
  (3a) Shopping cart
  (3b) shelves full of groceries
(4) Context specific ontology and meanings of concepts
  (4a) Ontology: *Reference to ontology #1-2-2*
  (4b) Concepts
    (LINGUISTIC-VARIABLE: *'Near'*; TYPE: *'spatial'*;
    MODEL: *buffer-zone*; FUZZY-MEM-FUNCTION: $f_1(\bullet)$)
(5) Goals to be focused on: *Respond to map request*
(6) Subgoals / tasks: *decide layers and extent of the map response*
(7) Events to be expected and handled:
  (7a) EVENT: *map requests involving spatial terms;* ACTION: *using this context to interpret the meaning of vague spatial term*.



In terms of the contents, our model of ontology space is general enough to capture multiple views and representations of the same geographical reality, and can certainly be used to capture the tiered ontology of Frank [23]. A contextualized ontology space is best constructed bottom-up, where ontologies for the most specific contexts (close to concrete experiences) are constructed first, followed by aggregation and generalization as necessary. An ontology space, when constructed from a well structured context space, can integrate different ontological approaches in a unified system. In particular, it can deal with the classical problem of GIS—namely the integration of vector and raster data [76]. Much of the work on geo-ontologies [12], [20], [39], [64], [69], [70] are relevant here but will not be repeated.

For the particular case of communicating vague spatial concepts, such as 'near,' we emphasize the use of contextualized ontology space to capture different levels of ambiguities in different contexts (similar to the idea of 'ambiguity contexts' in [31]). For example, Fig. 3 shows a possible contextualized ontology space where the concept 'near' is less ambiguous in $O_{1.1.1}$ than in $O_{1.1}$.

An ontology space based on contextualization can be represented either by traditional relational database [50], or by the Context OWL (or C-OWL) language as defined by Bouquet et al. [8]. Table 2 shows a relational implementation of the ontology space for the problem scenario of Fig. 1, which has a schema adopted from DOGMA [66]. Here the basic semantic unit is called 'Objects.' Each object is qualified by an ontology ID. Object1 and Object2 can be from two ontologies. 'Role' defines the relationship between the two objects in the row.

Table 2 A partial view of ontology space corresponding to Fig. 3

L-ID	Object1	Role	Object2
1	$O_{1.1}$	Subclass	O_1
2	$O_{1.1.1}$	Subclass	$O_{1.1}$
3	$O_{1.1.2}$	Subclass	$O_{1.1}$
4	O_1: near	Is_A	O_1: spatial relation
5	O_1: near	ModeledBy	O_1: buffer zone
6	$O_{1.1.1}$: near	Has	$O_{1.1.1}$: fuzzy member function $f_1(\ )$
7	$O_{1.1.1}$: near	SameAs	$O_{1.1.2}$: close to
8	$O_{1.1.2}$: near	MeasuredBy	Straight-line distance
9	$O_{1.1.1}$: near	MeasuredBy	Travel time
10	O_0: SC town	Reference	O_0: 'State College, PA'

3.5 Inter-ontology bridging rules: $\widehat{\Phi}$

On the top of context-partitioned ontological space, our model allows for the assertion of rules that 'bridge' any two ontologies (following the work of C-OWL [8]). This is especially useful when two ontologies (from different contexts) need to be integrated or related. Defining a bridging rule involves capturing the following features: (1) a unique identifier for this rule; (2) a reference to the source ontology; (3) a reference to the target ontology; (4) the source concept; (5) the target concept; and (6) a type of bridging relationship. These bridging rules are directional, which facilitate the translation of foreign elements into local semantic knowledge. We denote the whole set of rules as

$$\widehat{\Phi} = \left\{\Phi_{i,j} \middle| (i,j \in \{1,..,N\}) \text{ and } (i \neq j)\right\}$$

where N is the number of ontologies in the ontology space.

3.6 Inter-context bridging rules: $\widehat{\Psi}$

Contextual knowledge from one context can be made available to another context through inter-context bridging rules. This type of rules is also directional, which requires the identification of the source and target contexts, and the source and target propositions, with an indication of how they relate. This is useful when one agent reasons about the belief of another agent that 'resides' in a foreign context.

3.7 Context coordination rules: $\widehat{\Theta}$

An agent needs to constantly monitor the situation to perform context assessment. When new features or feature changes are observed, the agent will retrieve appropriate C-schemas as candidate contexts. Through a process of differential diagnostics, a new context object is created, which is used to guide subsequent behavior.

An agent must be able to use existing contextual knowledge to deal with new situations, even if the agent does not know a context that matches the current situation. The agent's knowledge about the strategies for dealing with novel situations is called *context coordination rules*. Here we focus on two kinds of such rules. First, contexts have the property of *composibility*. If the current situation can be characterized by several contexts (known to the agent), then the agent will compose or merge these contexts and give rise to a more complete assessment of the current situation. Knowledge about these contexts provides the basis for further interpreting sensory input and for generating behavior appropriate to the situation. Second, we adopt a *spreading activation* rule when assessing a situation against known contexts. When a situation is not clearly mapped to a knowledge context, all the contexts that have a consistent explanation of the observed features of the current situation are activated.

3.8 Ontology coordination rules: $\widehat{\Omega}$

After the two communicating agents establish coordination at the context level, they may still find that their ontological commitments are different. The agents must decide how to coordinate their ontological commitments so that semantic interoperability can be achieved. Previous semantic reconciliation approaches [26], [37], [41] rely on the discovery of an anchoring ontology which serves as boundary semantic object between the two heterogeneous systems. Such a purely ontology-oriented approach will not work for a highly context-dependent domain such as geographical information science, since the semantic reconciliation strategies are also likely to be context-dependent [55].

Our CMSI-G framework has a much richer set of coordination mechanisms that can circumvent the limitations of context-independent ontologies. Contexts serve several unique roles when ontologies need to be coordinated:

(1) *Contexts provide the necessary metadata knowledge that help establish bridges between two different ontologies*. One of the important components of context is the joint activity between cooperating agents. An activity-centric view of context [57] can effectively relate information sources and their ontologies to various parts of an activity. This role of contexts has not been exploited in knowledge management and information interoperability. This topic will be further explored in Section 4.
(2) *Contexts narrow down the search scope for discovering common semantic anchors*. When a shared ontology is impossible, contexts (when shared) provide a constrained domain where local interpretation of foreign concepts is discovered.
(3) *Contexts create opportunity for emergent data semantics*. Shared contexts allow semantic agreements to be established ‘on-the-fly’ (during the time of interaction) rather than relying on pre-existing consensus.

The above discussion on context-mediated ontology coordination coincides with the idea of emergent semantic systems [1], which is exactly what is needed for geographical applications. The CMSI-G framework lays a foundation for emergent semantics. However, we need a computational architecture that can support the fluidity of emergent semantics. This is the goal of the next section.

4 Towards dialogue-assisted context mediation of semantic interoperability

We have partially implemented the CMSI-G framework in the *GeoDialogue2* environment (see Fig. 2). This involves structuring the knowledge-base of *GeoDialogue2* using C-schemas, and interpreting each dialogue exchange in the scope of local contexts. This implementation addresses two major computational issues when the CMSI-G framework is operationalized. The first issue is about *how to represent each context adequately in order* *to support different granularities of contexts*. In the specification of CMSI-G framework in Section 3, we capture contextual knowledge as C-schemas within which contexts are described as if they are simple list of features. This is not adequate since features of a context are themselves highly structured. The objective of Section 4.1 is to present an activity-centered view of context.

The second issue, which is dealt with in Section 4.2, is about *how to accomplish successful context assessment and semantic coordination when there is a lack of shared contextual knowledge*. Here we emphasis the use of mixed-initiative dialogues as the key mechanism for context assessment and semantic negotiation.

4.1 An activity-centric model of contexts

Agents involve semantic exchanges for some purposes. The set of general and specific purposes that motivate the semantic exchange between two agents defines the ongoing activity. Since the success of a semantic exchange is ultimately judged by how well the underlying activity is supported, we propose that “activity” (following the notion of activity theory [53]) should be used as the basis for integrating knowledge from the two agents. In the context of this paper, we define an activity as *a coordinated set of goals together with the necessary set of mental states (beliefs, intentions, and commitments) of the interacting agents and environmental conditions that ensure the success of the shared goals*. This definition effectively ties all the physical and cognitive features of a context to the elements of an activity.

Situated actions [67] and Activity Theory [53] inform us regarding the fluid and ever-changing nature of physical situations and human activities. In *GeoDialogue2*, we capture this aspect of an activity by computationally representing an activity as a SharedPlan (see Fig. 4), following the seminal work of Grosz and Kraus [28]. A SharedPlan consists of a set of complex mental attitudes (beliefs, intentions, and commitments) towards a joint goal and its subgoals. Before agents start an activity, the SharedPlan of the activity is initially empty. As agents propose new initiatives (recognizable from their dialogue exchanges), new plan nodes are introduced. The ‘root plan’ of the SharedPlan represents the most encompassing goal mentioned so far. If action of the root plan is complex, agents will elaborate it into a more detailed plans by selecting a “recipe” (i.e., knowledge about a way to achieve a goal). At any moment, agents focus attention on one part of the plan for elaboration. If a subaction is not directly executable (i.e., a complex action), a subplan will be formed for performing this subaction. These subplans may themselves be complex, and will become the subjects of further elaboration.

The progression of an activity corresponds to the process of evolving the SharedPlan from a partial one towards a full SharedPlan [44]. A SharedPlan become a *Full SharedPlan* (FSP) when (1) participating agents share the belief that everyone intends and is committed to the whole plan; (2) all actions on the leaf-nodes are basic actions; and (3) for each of the parameters, that either it is instantiated already, or that agents have a Full SharedPlan (FSP) for identifying the parameter. If the above conditions are not met, we say that the plan is only a *Partial SharedPlan* (PSP). A PSP represents an ongoing activity, while a FSP represents a completed activity.

4.2 The roles of dialogues in the mediation of semantic interoperability

The mixed-initiative dialogue capability of GeoDialogue2, in combination with the CMSI-G framework, provides open-ended opportunities towards meaningful exchange of

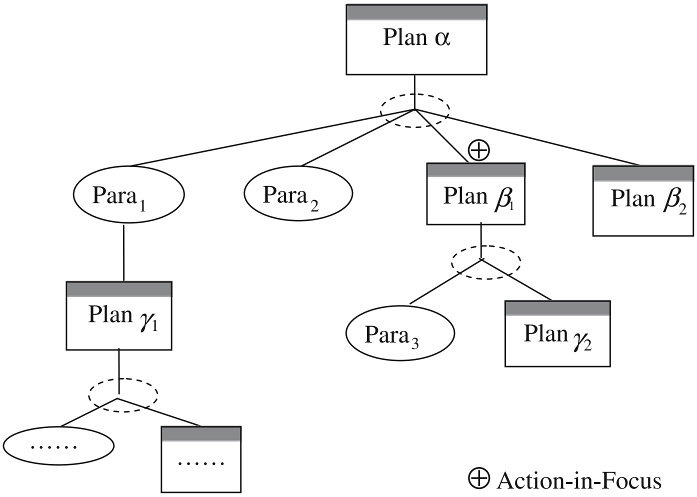


Fig. 4 Structure of a activity represented as a SharedPlan (after [11])

geospatial information. Here, we highlight a few prominent roles that a mixed-initiative dialogue system (such as GeoDialogue2) can play:

(1) *Dialogue Assisted Context Assessment*. Context assessment in GeoDialogue2 involves activating C-schemas based on the recently observed features of the situation, followed by a progressive diagnostic process. When new observations of situation is available, GeoDialogue2 not only generates a hypothesis about the context of the current situation based on observed features, but also predicts (using the contextual knowledge in the C-schema) what features are likely to be true (but not known yet) if the hypothesis is true. When multiple hypotheses are pending (thus causing ambiguity in subsequent actions), GeoDialogue2 is capable of initiating context diagnostic process through which further knowledge about the current situation is elicited and used to refine context assessment. For example, if a user's request ("Show me a map of groceries near SC town") included task and spatial context information but there is no mention about the transportation tools, the context assessment module may find more than one candidate context schema. In order to narrow down further to the right context, GeoDialogue2 will generate an initiative by asking "*how would you travel for shopping?*" This question is based on the knowledge that the current context object has one definition feature unknown.

(2) *Dialogue Assisted Context Coordination*. Context coordination involves making sure that the two communicating agents are fully aware of the shared context. Since GeoDialogue2 keeps track of what contextual knowledge has been shared by the SharedPlan of the ongoing activity. The lack of context coordination can be detected easily by inspecting the SharedPlan. Those plan-nodes that do not have mutual beliefs from both agents represent needs for further coordination.

(3) *Dialogue Assisted Ontology Coordination*. As discussed in Section 3.7, the lack of common ontological commitment among two agents can be circumvented by discovering the linkages of their local ontologies to the shared activity. Again, GeoDialogue2 offers three kinds of support: (1) it provides a sufficient model of the current activity, (2) it reasons on potential relationships between the two local ontologies and generate

hypotheses on the possible semantic anchors, and (3) it confirms and grounds such hypotheses through negotiation.

5 Discussion and conclusion

We have developed a new semantic model that overcomes the limitations of pure ontology-based approach in dealing with geo-semantic interoperability. The central idea is to put contexts and contextualization into the center of semantic modeling and semantic coordination. The main contribution of the paper is the description of a framework CMSI-G (Context-Mediated Semantic Interoperability for Geographical information) and a dialogue-based computational mechanism for context mediation in human–GIS interactions. This work is based on a careful analysis of the literature and established work on contextualization and ontologies.

This work represents an initial step of our larger goal towards addressing the problem of context-dependent geosemantics, and can only be considered as a rough outline of the CMSI-G framework. There are still many details to be developed before we can fully claim the expected advances. Future work will involve development and assessment of novel human–GIS dialogue behavior as induced by context reasoning capability. Methods of knowledge elicitation for context analysis and abstraction are also an important research area. Although human–GIS interaction is used in this paper as the initial domain of application, the principles behind the method described are expected to be equally effective to other semantic problems, such as spatial data sharing and integration, but we will leave that for future studies.

Acknowledgments This material is based upon work supported by the National Science Foundation under grants no. EIA-0306845 and BCS-0113030. The author thanks two anonymous reviewers for their insightful suggestions. Final version of this paper benefited from a read by David J. Saab who helped improve the quality of the language.

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