AGENT-BASED MODELING OF COMPLEX SPATIAL SYSTEMS WORKSHOP POSITION PAPER

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Virtually all current scientific, socioeconomic and security questions depend on geospatial information and on the ability of scientists to interact with that information in increasingly flexible and holistic ways, whether the problem context concerns, for example, managing urban growth, predicting the spread of disease, understanding an evolving world economy in the digital age or protecting against terrorist attack.

The important issues relating to these applications center on the understanding of geospatial *processes*, as entities change over time. The interactions among entities and their components within processes tend to be highly dynamic, interlinked, and with complex chains of cause-and-effect. For example, environmental water quality is affected by urbanization (housing and road density, etc.), which is in turn affected by public policy and economics governing how and where things may be built at both local and regional scales.

Because of the complex and non-deterministic interactions of social and natural components, improving our understanding of geospatial processes or deriving specific problem solutions generally requires representation and analysis of higher-level, domain-specific human knowledge in addition to observational data. The complexity of the processes being investigated also requires the application of expertise from multiple knowledge domains. How do the components of a process and the subcomponents of each relate to each other, and at varying spatio-temporal scales? Such questions are addressed via teams of analysts with differing domains of expertise and differing views of the phenomenon. Because of the limitations of current tools, their analyses tend to be unlinked and potentially in disagreement.

Approaches for representation and analysis remain focused on handling observational data. The current manifestation of this focus is the emergence of networks for the purpose of linking various data sources and software tools, and providing real-time access to these, via what has become known as the *cyber-infrastructure*. Higher-level, derived knowledge of geographic phenomena is rarely stored or utilized by the software. As pointed out by [1], GIScience has been focused on the study of *form* – of how world looks rather than how the world works. What can be derived from current geospatial software tools is thus limited by the expertise, experience, and memories of the specific people using the system at a given time. This can be problematic, particularly in an emergency situation when a solution must be quickly derived.

Formalized ontologies are widely seen as the means to overcoming this situation, and have received much attention within GIScience. Ontologies, in a digital context, provide a basis for augmenting data with a common semantics for database integration and sharing, as well as a stored knowledge base. These formalized ontologies are often described conceptually (and represented graphically) as concept graphs. While this approach provides a means of representing a level of abstraction above the observational data that is also intuitive for the user, it is not without serious shortcomings with regard to representing space-time process, as well as refining our knowledge of processes through new observational data.

Formalized ontologies tend to be built through a manual, custom-tailoring process. They may grow as users add concepts and relationships but the basic concepts and interrelationships among them are assumed to be static. In the real world, however, concepts evolve - the basic categorical groupings from which they derive change, concepts can be replaced or completely redefined, as well as the relationships among them – as knowledge grows.

OWL has quickly become the standard language for encoding formalized ontologies. OWL is a Web Ontology Language intended as a tool for providing a means for common understanding across the World Wide Web in the idea of the 'semantic net.' OWL was designed to define classes and concepts as well as their properties and relationships, and also to allow reasoning about these classes and concepts [2]. It, however, is weak in its operational ability to determine the need for change in the ontology represented via evidence from new data and to appropriately modify it. The volume of new geospatial data streaming in from various sources, and their heterogeneity (with the consequent complexity and variability of possible patterns) makes a focus on inductive techniques such as those associated with Data Mining insufficient. Theory-driven methods of analysis that are guided by stored knowledge, as well as observational data, are required.

As already stated, ontologies provide a specification of classes, concepts and the structure among them. Recent research has shown how this can be extended to include ontological history – explicit storage of new and superseded concepts, these linkages, and description of how components originate [3]. Nevertheless, the fundamental mechanisms of the underlying *process* – i.e., how things change and evolve to affect the form of the observed phenomenon and the derived, abstracted elements (or concepts) within that process – is not represented within any ontology. A process can be defined functionally as a function that acts on a domain and may or may not refer to, or act upon, observed objects applicable to the domain (a specific instance of, for example, a city, disease, or multinational corporation) stored within the data. The process could be simple and elemental (e.g., move forward), or could be more complex (shoreline erosion), in which case, it is composed from a dynamic set of hierarchically organized functions. Generally speaking, such a function incorporates a description of behaviors and their applicable context along with defined triggers to specific behaviors. Such a description would often consist of rules. At an elemental level, a function could be an algorithmic or mathematical transformation.

So, just as it is now acknowledged that storing large amounts of heterogeneous geospatial data requires a multi-representation framework, storing higher-level information concerning geospatial phenomena and their dynamics also requires a multi-representation approach. Moreover, these multiple data and knowledge representations must be functionally interlinked. Initial research at Penn State [4] has shown that the use of multiple software agent types linked with an ontology and database utilizing a what/when/where schema provides the needed combination of representational power.

There has been growing recent interest in intelligent software agents in GIScience as a specific tool in a variety of contexts, including simulation of land-use/cover change [5], wayfinding [6], and social simulations [7]. Software agents are not only a natural way to represent social aspects (institutions, societies, etc.) as well as natural aspects (climate, hydrology, etc.) of geospatial processes, but also to represent the coordinated dynamic behaviors of multiple entities constituting complex dynamic processes. They, in combination, can be applied in simulations of space-time processes to provide a key means of representing a specific process (or components of a process at a specific scale) in a dynamic way that deals with complex interactions [8].

Cognitive agents, as opposed to reactive agents, maintain an internal state (e.g., goals, plans, and state information about the world), and behave by searching through a space of behaviors and cooperating with other agents (which in turn may affect their actions)[9]. Key properties of cognitive agents with these characteristics are that besides being *situated* (applicable, or active, within specific contexts) and *distributed* (maintain their own constrained view), they are *adaptive* (learn and improve through experience). Cognitive agents can thus also be viewed as corresponding to the expertise of a human expert. Reactive agents tend to be more algorithmic in nature and are thus appropriate for dealing with low-level functions. A middle form (not fully cognitive) can also be useful as a flexible means of representing, various components of those processes.

Such a multiple agent scheme provides a means of representing knowledge about process (captured through simulation and verified via linkage with observational data, or explicitly input by the user). Agents, in combination with ontologies, act as knowledge carriers to provide qualitative information, derivation of higher-level abstractions, and makes large stores of observational data more easily retrievable, reusable, and shareable. This provides for a powerful simulation environment for studying space-time dynamics, but more importantly, such simulations provide a means of analyzing "what-if" alternatives to aide the human analyst/decision maker, and a fast means of conveying domain-specific knowledge to decision-makers in time-critical situations.

References

1. Goodchild, M., *GIScience, Geography, Form, and Process.* Annals of the Association of American Geographers, 2004. **94**(4): p. 709-714.
2. Aref, M.M. and Z. Zhou. *The Ontology Web Language (OWL) for a Multi-Agent Understating System*. in *International Conference on Integration of Knowledge Intensive Multi-Agent Systems (KIMAS 2005)*. 2005. Boston: IEEE.
3. Brodaric, B., *Representing Geo-Pragmatics*, in *Ph.D. thesis, Department of Geography*. 2005, Penn State University: University Park, PA.
4. Yu, C., *Geoagent-based Knowledge Systems, Ph.D. thesis, Department of Geography*. 2005, Penn State University: University Park, PA.
5. Parker, D.C., T. Berger, and S.M. Manson, *Agent-Based Models of Land-Use / Land-Cover Change*, in *LUCC Report Series No.6*. 2001, LUCC Focus 1 Office Anthropological Center for Training and Research on Global Environmental Change, Indiana University.
6. Raubal, M., *Ontology and epistemology for agent-based wayfinding simulation.* International Journal of Gegraphical Information Science, 2001. **15**(7): p. 653-665.
7. Conte, R., et al., *Sociology and social theory in agent based social simulation: a symposium.* Computational and Mathematical Organization Theory, 2001. **7**: p. 183-205.
8. Jennings, N.R., *On Agent-Based Software Engineering.* Artificial Intelligence, 2000. **117**(2): p. 277-296.
9. Ferber, J., *Multi-agent systems: an introduction to distributed artificial intelligence*. 1999, New York: Addison-Wesley.