Position Paper for Agent-Based Models of Complex Systems*

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Object-oriented process models, which include individual-based models (IBM) commonly used in ecology and agent-based models (ABM) common in the social sciences, allow for modeling both change and movement of geographic entities and have developed independently of GIS. The object-oriented framework of ABM involves identification of agents and of a temporal framework within which those agents perform actions. While many different types of agents can exist, the following general definition is common: an agent is a self-directed object, i.e., it has the ability to satisfy internal goals or objectives through actions and decisions based on a set of internal rules or strategies. These agents may be dynamic in either state (i.e., change) or space (i.e., movement) and may, through their actions, change the state or location of other objects, processes, or environments around them. Agent dynamics are most naturally implemented in an ABM by a set of behaviors ("methods") that can include conditional decision making and other (non-linear) rules that distinguish them from mathematically continuous models. The ability for Lagrangian motion (i.e., agent movement) distinguishes ABM and other object-oriented modeling frameworks from the change-based spatial models described above. It also creates additional challenges for integrating these models with GIS, as described in more detail below.

ABM dynamics are defined at the level of (a) agent behaviors that result in change and movement, and (b) the independent dynamics, if any, of non-agent objects. Thus to represent dynamics, ABMs are implemented as discrete event simulations, in which some kind of "scheduling" mechanism handles the sequencing of agent behaviors and events. An ABM may implement scheduled events in three ways:

- Events may be sequenced in a synchronous step-wise fashion. For example, each agent, set of agents or non-agent object is signaled to perform its tasks once at each time step or once every *n* time steps.
- An event may be scheduled to occur only once at some time step *n*. Any number of different events may be scheduled to occur in this fashion providing a predetermined history of events to take place.
- The model may encapsulate 'event-driven' processes whereby model agents may trigger events to occur or may add events to the schedule or queue of events to take place.

On the other hand, ABMs often use relatively limited representations of space. For example, ABMs frequently use hypothetical spaces based on square or hexagonal tessellations, and only recently have ABMs begun to use real-world spatial data. To avoid edge effects on the performance of some models, researchers commonly use a toroidal representation of space, which wraps around from top-bottom, left-right, and vice versa. The rich temporal representations (agents and processes) of agent-based models, therefore complement the spatial data representations (fields, objects and functions) of GIS. The object-oriented nature of both presents tremendous opportunities for their integration.

Given the complementarities of spatial data models (fields and objects) and agent-based (i.e., object-oriented) process models, and their combined potential to improve on integrated representations of spatial patterns and temporal processes, we argue that tight coupling of models and data within ABM and GIS, respectively, can reap benefits in terms of both efficiency, through reduced computing times, and capability, through new functionality. Attempts to integrate ABM and GIS techniques have raised several conceptual and technical questions. These issues broadly fall into questions of ontology and process, i.e., how are entities and processes represented, and how do those representations interact, respectively. For instance, Bian (2003) concluded that the environment within an individual-based model can be represented as either patch-based (i.e., object-based), maintaining object-orientation in both the model and data, or field-based, such that object-oriented individuals interact with a discretized environment of attributes. She discounts the value of treating all cells in a grid-based environment as objects on both technical (i.e., due to inefficiencies) and ontological (i.e., poor match to conceptual view of fields) grounds.

More generally, developing models that make use of both GIS and ABM techniques requires the specification and implementation of relationships between agent-level processes and spatial data. First, by defining an *identity relationship* between an agent and a spatial feature or features, GIS techniques can be used to store the geographic extent and attributes of the feature, while ABM techniques represent the behavior of the agent and the change in associated feature(s). Thus (a) spatial features associated with agents can move or change, and (b) attributes of features associated with agents can change. Second, in many models, agents have *causal relationships* with (i.e., the ability to take actions that affect) spatial features and/or their attributes, even if there is no identity association between the agent and the spatial feature(s) it is acting on (i.e., non-agent features). Agents can take actions that result in changed locations or attributes of features, or they can take actions that change the values of an attribute on a field (e.g., a raster). Third, *temporal relationships* are inherent in two types of actions in a coupled process-data model: (a) the actions of the agents and (b) the updating of attributes or locations of features in a database or display. Either can be handled using synchronous or asynchronous approaches. Finally, movement of spatial features, either by processes internal to their associated agents or by those of other agents, can require basic information about the *topological relationships* between an agent and the physical world or between features.

We have been working on a number of different approaches to implementing the object-based process models that are linked to dynamic spatial data models. The simplest approach has been to loosely couple agent-based process models, with GIS data bases by passing interchange files between the two. A significant disadvantage of this is the volume of data created by the models and the consequent data-management challenges. Secondly, we participated in the testing of AgentAnalyst, an extension to both RePast and ArcGIS and other GIS systems (like OpenGIS) that serves as a sort of middleware to link the two. There are limits to its ability to dynamically use of GIS functions, unless connected to open source GISs. This places greater burden on the modeler to program GIS functions within the model. Finally, we have a model written in VBA and running completely within ArcGIS, which takes fuller advantage of GIS functions, but requires that ABM functions (like the scheduler) be programmed into the model (rather than relying on existing software libraries). New dynamic modeling functions within GIS environments, like those in PCRaster for raster data, will significantly improve these capabilities within next-generation GISs.

* mostly excerpted from Brown, D.G., Riolo, R.L., Robinson, D., North, M., and Rand, W. Spatial process and data models: Toward integration of agent-based models and GIS. *Journal of Geographical Systems,* 7(1): 1-23.