Oral Comprehensive Exam Study Plan: Simulating Processes with Spatial Variability

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1 Introduction

Ecological processes play a critical role in shaping the world in which we live and guiding our interactions with it. As humans we are consistently attempting to predict, understand and sometimes control the behaviour of the natural world. Whether we are trying to forecast the upcoming seasonal rains, recreating a forest fire to understand why it burned in a particular manner, or making land management decisions towards a particular future objective, computer models and simulations can be of crucial assistance.

The discipline of computer simulation, whether the simulated processes be computer related, business oriented, ecological, etc., is a discipline as old as computing and is well understood. Accurately and efficiently simulating time (as discrete events) is also well understood. However, many processes, particularly ecological processes which are ongoing over a large spatial range have a spatial component which substantially increases the time and complexity of the computations involved.

To date most of the existing work in spatial modeling is raster-based; also known as grid-based. Raster-based models contain a spatial array of fixed-size entities for which every computation must be run at each time step interval. This presents a paradox where the accuracy of the simulation may require a fine grained spatial scale, but the application may require a fast input/output turn around to have usable results. These goals are in tension and we believe that there exist more efficient methods of modeling space to achieve both accurate simulations and efficient computation.

To research more efficient methods of spatial modeling one must have a firm understanding of several different areas. In this paper we define our research area: **variable resolution spatial modeling**. We describe the how the problem of accurately and efficiently simulating time has been solved and draw a parallel for how we anticipate solving the problem of simulating space. We then outline the requirements for understanding the key problems and open research questions. We then propose a reading list and study plan for the Oral Comprehensive Exam, a requirement set forth by the Graduate Education Committee.

2 Research Area Definition

Our research area, **variable resolution spatial modeling**, is an integrative discipline that requires researchers to have a firm grasp on both *modeling and simulation* as well as one or more *application areas*.

To become an effective researcher in this area, one must be well versed in all recent advancements in both spatial and temporal modeling and the ecological applications areas. Having a working knowledge of both subject matter will allow the researcher to address fundamental problems in modeling and simulation. One can then contribute new ideas which will advance the state of modeling and simulation and provide better applications for the ecological problems. In essence we start with the application area, allow that to direct our modeling and simulation efforts, which then also advance the application area.

In the following sections we outline recent advancements in temporal modeling, spatial modeling, and applications areas which must be understood to research and make further contributions to **variable resolution spatial modeling**.

2.1 Computer Simulation

2.1.1 Types of Simulation

Law and Kelton [1] subdivide computer simulation along several different axes. Types of simulation are generally differentiated as being either static or dynamic, either deterministic or stochastic, and either continuous or discrete. In complex systems such as ecological systems, both sides of each division are often employed to create a complete model. For example, in modeling fire behaviour the distance over which a ground fire spreads in a particular time interval is deterministically calculated. However, whether or not the fire *spots* (i.e. whether embers are blown ahead of the fire front, creating a new fire) is generally modeled as a stochastic event.

In spatio-temporal modeling of ecological processes we are dealing with primarily dynamic models. These models may contain both deterministic and stochastic elements and may contain both continuous and discrete elements. It is important for a researcher in this area to be knowledgeable in each of these subdivisions of dynamic computer simulation.

2.1.2 Simulating Time

Simulating the passage of time accurately and efficiently is a problem that is well understood and has primarily been solved. It is, however, important for a researcher of dynamic spatial models to understand these techniques of simulating time. We also anticipate using the existing solutions of simulating time as an analogy for solving the problem of accurately and efficiently simulating space.

Currently, there exist two main methods of simulating the advancement of time in dynamic computer simulation. Both methods, *fixed increment* time advance and *event driven* time advance are actively employed in modeling ecological processes. This elicits the need for both methods to be part of a researcher's knowledge base.

In a fixed increment time advance simulation, the global clock is advanced at discrete, regular intervals. Events that occur between intervals are assumed to occur at the discrete, regular time intervals. Several of the most recent fire behaviour simulators, particularly FARSITE [2] and BehavePlus [3], simulate Rothermel's continuous model for the spread of a ground fire [4] by calculating the distance traveled by the fire front during a discrete time step.

In event driven time advance, sometimes known as Discrete EVent Simulation (DEVS), the clock is advanced forward to the time at which the next event will take place. This method has long been applied in simulating queuing systems and business processes. More recently researchers have begun to realize that using an event driven time advance can be beneficial to ecological applications. For instance Ntaimo et. al [5] use DEVS to efficiently simulate the spread of forest fire and obtain timely results.

We are particularly interested in DEVS approaches because event based simulation essentially allows a **variable temporal resolution**. When few to no events are occurring (for example few fire events occur during the eight months of a wet winter) time can be forwarded with little computational overhead. However, when a series of complex events are occurring (for example during a highly complex patchwork of mosaic forest fires) time is slowed down and the results of events are accurately computed. In future research we are interested in taking this variable resolution approach to time and using it on space.

2.1.3 Simulating Space

Unlike many processes-oriented simulations (e.g. queueing systems) which are often modeled using DEVS, we are interested in *spatially explicit models*. A spatially explicit model is one in which all of the many entities involved have explicit spatial locations, and there is some relationship between locations which affect the simulation process and results [6]. We consider most landscape ecological processes to be spatially explicit.

In contract the vast majority of existing computer simulation is process-oriented simulation. This is generally defined as a simulation where some entity follows through a time sequenced process of events [1]. Examples would include an n server queuing simulation or a simulation of a network routing protocol.

Most landscape simulations *do* involve some process of events, but in general we define process-oriented simulations to be absent of any spatial explicitness.

Currently the vast majority of spatially explicit modeling uses a *raster-based* (also known as grid-based) approach. There is also some existing work with a related method called *cellular automata*. Additionally there exist *polygon-based spatial* (PBS) models and continuous spatial models.

Raster-based models, where a grid is placed over the two dimensional spatial domain, are an obvious choice in spatial modeling due to their simplicity and ease of understanding. In the closely related method of cellular automata modeling used by Costanza et al. [6], each grid entity has its own series of data and inter-cell processes that govern it (leading to strong modular model design). The problem with these approaches, however, is that as the detail required by the model becomes more fine-grained, the sheer number of input data, output data, and computations can sometimes make the simulation infeasible.

Polygon-based spatial (PBS) models (sometimes known as lumped spatial models), as used by Boumans and Sklar [7] are a more simplified version of raster-based models, where many cells are clumped together into polygons. Spatial properties are then assumed to be constant across an entire polygon rather then only one grid cell. This reduces the number of distinct data and calculations required in a simulation, but also drastically reduces the accuracy of what can be complex system dynamics. This approach is, however, the closest work that we have seen to a method of modeling using **variable spatial resolution**.

Finally, a number of statisticians including Higdon [8] are working on continuous spatio-temporal models using process convolutions. While we envision our work to be more closely related to discrete, variable resolution models, we include this work in our reading list for ideas to be draw from.

2.2 Data Structure and Storage

Also pertinent to researching spatial modeling is the question of data structure and storage. Since the early 1990's, a significant amount of work has been done in developing spatial data structures and spatial databases. If one is to develop efficient variable resolution spatial models, one must be knowledgeable about existing work in spatial data structure and storage. For this reason we include in our reading list several texts and articles from this sub-area.

2.3 Applications

As we described in the beginning of Section 2, it is important for a researcher in this integrative area to have a firm grasp on the application area in order to propose applicable advances in computer modeling and simulation. As part of our required reading list, we propose a number of fundamental papers and texts in our most compelling application areas: fire behaviour and fire ecology.

We envision many other areas to which one could apply variable resolution spatio-temporal modeling in addition to those which are fire-related. A few landscape examples which could have both spatial and temporal components are modeling ecosystem succession over time, predicting future weather pattern, predicting genetic drift of genetically modified organisms, or tracking the spread of a particular disease across a landscape.

There are many other non-landscape related disciplines which use spatial data and to which this research could be applied. The development of ad-hoc wireless routing algorithms frequently use simulation. There are also medical applications such as 3-d image reconstruction and path planning applications such as road network design, orienteering and navigation [9].

3 Reading List

3.1 Computer Simulation

- A. M. Law and W. D. Kelton, *Simulation Modeling and Analysis*, 3rd ed., ser. McGraw-Hill Series in Industrial Engineering and Management Science. McGraw-Hill Companies, Inc., 2000.

- B. P. Zeigler, H. Praehofer, and T. Kim, *Theory of modeling and simulation*, 2nd ed. New York: Academic Press, 2000.

3.1.1 Simulating Time

- L. Ntaimo, B. P. Zeigler, M. J. Vasconcelos, and B. Khargharia, "Forest fire spread and suppression in DEVS," *Simulation*, vol. 80, no. 10, pp. 479–500, October 2004.

3.1.2 Simulating Space

- R. Costanza and A. Voi, Eds., *Landscape simulation modeling: a spatially explicit, dynamic approach*, ser. Modeling Dynamic Systems. Springer-Verlag, 2004.
- R. M. Boumans and F. H. Sklar, "A polygon-based spatial (PBS) model for simulating landscape change," *Landscape Ecology*, vol. 4, no. 2, pp. 83–97, 1990.
- D. Higdon, "Spatial and spatio-temporal modeling using process convolutions," March 2001.
- A. Muzy, E. Innocenti, J.-F. Santucci, and D. R. Hill, "Optimization of cell spaces simulation for the modeling of fire spreading," in *36th Annual Simulation Symposium*, March/April 2004.
- G. Wainer and N. Giambiasi, "Timed cell-DEVS: Modeling and simulation of cell spaces," in *Discrete event modeling & simulation: Enabling future technologies*, H. Sarjoughian, Ed. New York: Springer-Verlag, 2001, pp. 187–213.
- J. Ameghino, A. Troccoli, and G. Wainer, "Models of complex physical systems using cell-DEVS," in *Proceedings of the Annual Simulation Symposium*, 2001.
- E. Rastetter, A. King, B. Cosby, G. Hornberger, R. O'Neill, and J. Hobbs, "Aggregating fine-scale ecological knowledge to model coarser-scale attributes of ecosystems," *Ecological Applications*, vol. 2, pp. 55–70, 1992.
- J. Vasconcelos, "Modeling spatial dynamic ecological processes with DEVS-scheme and geographical information systems," Ph.D. dissertation, University of Arizona, Tucson, Department of Renewable and Natural Resources, 1993.
- T. Rosswall, R. G. Woodmansee, and P. G. Risser, Eds., *Scales and Global Change: Spatial and Temporal Variability in Biospheric and Geospheric Processes.* Weiley, New York, 1998.
- D. Steyn, T. Oke, J. Hay, and J. Knox, "On scales in meteorology and climatology," *Climate Bulletin*, vol. 39, pp. 1–8, 1981.
- V. Meentemeyer, "Geographical perspectives of space, time and scale," *Landscape Ecology*, vol. 4, no. 3-4, pp. 163–173, 1989.

3.2 Data Structure and Storage

- H. Samet, *The Design and Analysis of Spatial Data Structures.* Addison-Wesley, Reading, MA, 1990.
- H. Samet, *Applications of Spatial Data Structures: Computer Graphics, Image Processing, and GIS.* Addison-Wesley, Reading, MA, 1990.

- M. Egenhofer, "A topological data model for spatial databases," in *Proceedings of the first symposium on Design and implementation of large spatial databases*, 1989.
- W. Aref and H. Samet, "Extending a dbms with spatial operations," in *Proceedings of the Second International Symposium on Advances in Spatial Databases*, 1991.

3.3 Application Areas

3.3.1 Fire Ecology

- M. Fuller, *Forest Fires: An Introduction to Wildland Fire Behavior, Management, Firefighting, and Prevention.* John Wiledy & Sons, Inc., 1991.
- R. J. Whelan, *The Ecology of Fire.* Cambridge University Press, 1995.
- S. J. Pyne, P. L. Andrews, and R. D. Laven, *Introduction to wildland fire*, 2nd ed. New York : Wiley, 1996.

3.3.2 Fire Behaviour

- R. C. Rothermel, "A mathematical model for predicting fire spread in wildland fuels," USDA Forest Service, Research Paper INT-115, January 1972.

3.3.3 Existing Modeling

- M. A. Finney, "FARSITE: Fire area simulator–model development and evaluation," USDA Forest Service, Rocky Mountain Research Station, Tech. Rep. RMRS-RP-4, March 1998.
- P. L. Andrews, C. D. Bevins, and R. C. Seli, "BehavePlus fire modeling system version 2.0 user's guide," USDA Forest Service, Rocky Mountain Research Station, Tech. Rep. RMRS-GTR-106WWW, June 2003.
- H. S. He and D. J. Mladenoff, "Spatially explicit and stochastic simulation of forest-landscape fire disturbance and succession," *Ecology*, vol. 80, no. 1, pp. 81–99, 1999.
- A. Muzy, G. Wainer, E. Innocenti, A. Aiello, and J. Santucci, "Comparing simulation methods for fire spreading across a fuel bed," in *Proceedings of AIS'2002, Lisbon, Portugal*, 2002.

4 Timetable and Deliverables

As outlined by the Graduate Education Committee three deliverable are required for the Oral Comprehensive Exam: an oral comprehensive study plan (this document), a position paper, and an oral presentation and defense. I plan on filing the study plan contained herein once I have obtained a sufficient number of committee members with the appropriate backgrounds (see Appendix B for potential members). Other deliverables are targeted for completion according to the schedule below. The position paper will be given to committee members at least two weeks before the public presentation, in order to allow them sufficient time to suggest changes. Note that the times may change in order to meet the needs of the student and the committee.

Deliverable	Target Date
Study plan	April 29, 2005
Position paper	November 11, 2005
Oral defense	November 25, 2005

References

[1] A. M. Law and W. D. Kelton, *Simulation Modeling and Analysis*, 3rd ed., ser. McGraw-Hill Series in Industrial Engineering and Management Science. McGraw-Hill Companies, Inc., 2000.

[2] M. A. Finney, "FARSITE: Fire area simulator–model development and evaluation," USDA Forest Service, Rocky Mountain Research Station, Tech. Rep. RMRS-RP-4, March 1998.

[3] P. L. Andrews, C. D. Bevins, and R. C. Seli, "BehavePlus fire modeling system version 2.0 user's guide," USDA Forest Service, Rocky Mountain Research Station, Tech. Rep. RMRS-GTR-106WWW, June 2003.

[4] R. C. Rothermel, "A mathematical model for predicting fire spread in wildland fuels," USDA Forest Service, Research Paper INT-115, January 1972.

[5] L. Ntaimo, B. P. Zeigler, M. J. Vasconcelos, and B. Khargharia, "Forest fire spread and suppression in DEVS," *Simulation*, vol. 80, no. 10, pp. 479–500, October 2004.

[6] R. Costanza and A. Voi, Eds., *Landscape simulation modeling: a spatially explicit, dynamic approach*, ser. Modeling Dynamic Systems. Springer-Verlag, 2004.

[7] R. M. Boumans and F. H. Sklar, "A polygon-based spatial (PBS) model for simulating landscape change," *Landscape Ecology*, vol. 4, no. 2, pp. 83–97, 1990.

[8] D. Higdon, "Spatial and spatio-temporal modeling using process convolutions," March 2001.

[9] "Spatial applications." [Online]. Available: http:\\atlas.scs.carleton.ca/~gis/projects/spatial_app/

A Journals, Conference Proceedings, and Workshops

- Simulation
- Winter Simulation Conference
- ACM/IEEE Annual Simulation Symposium
- Symposium on Advances in Spatial Databases
- Ecological Modeling
- Ecology
- Landscape Ecology
- European Conference on Ecological Modelling
- International Journal of Wildland Fire
- Joint Fire Science Conference and Workshop

B Human Resources

- Sarah A Douglas, Ph.D. University of Oregon Department of Computer and Information Science, Professor.
- Patrick Bartlein, Ph.D. University of Oregon Department of Geography, Professor.
- Timothy Ingalsbee, Ph.D. Western Fire Ecology Center, Director.
- Steven W Hostetler. Oregon State University, Geosciences, Courtesy Associate Professor (USGS).
- Daniel Udovic, Ph.D. University of Oregon Department of Environmental Studies, Biology, Professor.