

Parallel Agent-based Modelling of Land-Use Opinion Dynamics Using Graphics Processing Units

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1. Introduction

The objective of this paper is to present a parallel agent-based model of land use dynamics built on Graphics Processing Units (GPUs). Agent-based models (ABMs) provide a generative problem-solving framework (Epstein 1999; Brown et al. 2005) that employs agents, environments, and their interactions to simulate complex adaptive spatial systems (CASS; Bennett and Tang 2008). ABMs of CASS are often computationally intensive (Epstein 1997) because of the complexity of geographic systems and the need to represent massive agent-agent and agent-environment interactions. Most current ABMs and their supporting software are, however, based on single CPUs (central processing units). The problem size that these ABMs can address is often limited, therefore, by the need for reasonable execution times and the capacity of available computing resources (e.g., computer memory). Parallel and high-performance computing has been employed to overcome the computational limitations in ABMs. However, the cost and required technical knowledge associated with conventional high-performance computing limit its applicability. We illustrate that GPUs provide a viable high-performance computing alternative for parallel agent-based modelling of CASS.

GPUs, programmable graphics hardware devices originally designed for accelerating graphics processing operations, have developed into powerful co-processors that support general-purpose computation. These devices are flexible and offer significantly higher performance than traditional CPUs at a relatively low cost (Pharr and Fernando 2005). Based on a many-core computing architecture and data parallelism, GPUs employ a set of micro processors (or stream processors; see Buck et al. 2004) to enable parallel and high-performance computation. This architecture makes GPUs suitable for data- and compute-intensive problems (e.g., data mining, image processing, physical or chemical simulation, and numerical analysis; see Buck et al. 2004; Pharr and Fernando 2005). The high-performance computing capabilities of GPUs and the rapid development of associated techniques have stimulated applications in a wide array of domains, including biology, chemistry, and physics (see Pharr and Fernando 2005). Parallel computing platforms for GPUs, represented by CUDA (Compute Unified Device Architecture, see NVIDIA 2009b) and Brook (see Buck et al. 2004; Brook 2009), have undergone

significant development in recent years. For example, CUDA, compatible with various operating systems (e.g., Windows and Linux) and possessing a low learning curve (NVIDIA 2009a), provides considerable programming flexibility and access to the underlying parallel computing resources available in GPUs (NVIDIA 2009a). Researchers are becoming increasingly interested in exploiting GPUs' high-performance computing capabilities (which often outperforms CPUs by at least an order of magnitude; see Pharr and Fernando 2005) for resolving computationally intensive problems.

While GPUs are recognized as having tremendous problem-solving potential, the use of GPUs for supporting spatial simulation in general and ABMs in particular is still in its initial stage (Lysenko and D'Souza 2008; Richmond et al. 2009). It is thus important to investigate how the computing power of GPUs can be leveraged for ABMs of CASS. In this paper we discuss the development of a GPU-accelerated ABM that simulates opinion formation and diffusion about land use policy using CUDA to illustrate the capabilities of GPUs in enabling parallel agent-based modelling.

2. Methods

The agent-based model is designed to help investigate the rangeland dynamics of a rural county in western Montana. Land owners are modeled as geospatial agents who are situated within their parcels and interact within a spatially explicit environment and other agents in an attempt to achieve sustainable resource use. In particular, these agents exchange their opinions to reach consensus on land-use development policies, which affect future land use states and, thus, feedback back into the opinion dynamics of agents. We implement an opinion formation model (see Weisbuch et al. 2002) to simulate this process and tie the results of this model to a land-use change sub-model. In our model, agent opinion is represented as a continuous variable. Agent opinion change is characterized by a set of opinion parameters, including opinion exchange rate, and opinion threshold. An agent updates her/his opinions through interaction with other agents if the opinion difference between the two agents is within a predefined threshold. The development of opinion dynamics is influenced by heterogeneity in opinion parameters and agent interactions.

The modeling of opinion formation in our study area represents a computationally intensive problem because of massive individual-level interactions and the spatiotemporal complexity of rangeland systems. We use GPUs to accelerate our agent-based model, and CUDA as a parallel computing platform to harness the high-performance computing power available in GPUs. CUDA allows the use of a large number of threads (organized into a thread-block-grid hierarchy) each of which executes the same functions (i.e., kernel functions; see NVIDIA 2009a) to handle a sub-set of data stored in the device memory of GPUs, including global memory (grid-level), shared memory (thread block-level), and register memory (thread-level).

We developed a GPU-based parallel algorithm that maps our agent-based model to GPU devices by decomposing the set of agents, maintained in global memory (accessible by all threads) into groups, each of which is associated with a thread. These threads are then assigned to, and computed by, a set of processors in a GPU. GPUs enable the execution of a massive number of threads using hundreds of computing cores in parallel so as to achieve high-performance computation for agent-based modelling. In our GPU algorithm, agents associated with each thread update their opinions through interaction

with agents linked through dynamic social networks. The opinion exchange of agents in GPUs is performed by launching a set of kernel functions at each iteration and synchronizing the agents' behavioural update. In addition, we developed GPU algorithms of spatial metrics (e.g., entropy) for the parallel analysis and comparison of spatial patterns of agents.

3. Experiments

We designed a suite of experiments to evaluate the capabilities of GPUs in supporting parallel agent-based modelling. Performance metrics of parallel computing were employed to support this evaluation and we compared modelling results obtained from GPUs with those from CPUs (see Table 1 and Figure 1 for an example). We focused our investigation on the influence of agent and landscape characteristics on the computational performance of our parallel ABM. Our experimental results indicate that GPUs can significantly improve the computational performance of our ABM.

Landscape Size	CPU Time (Seconds)	GPU Time (Seconds)	Speedup
1,000	87	8.41	10.35
2,000	358	34.88	10.26
3,000	775	81.18	9.55
4,000	1,434	147.47	9.72
5,000	2,239	235.18	9.52
6,000	3,180	340.65	9.34
7,000	4,474	460.02	9.73
8,000	5,656	601.80	9.40
9,000	7,548	759.31	9.94
10,000	8,709	938.36	9.28

Table 1. Performance comparison for CPU- and GPU-based ABM in response to landscape size (AMD Opteron processors with 2.4GHz of clock rate were used for CPU computation; Tesla T10 GPU (1.3GHz clock rate and 240 cores) was used; speedup is a performance metric obtained by dividing parallel execution time by sequential time).

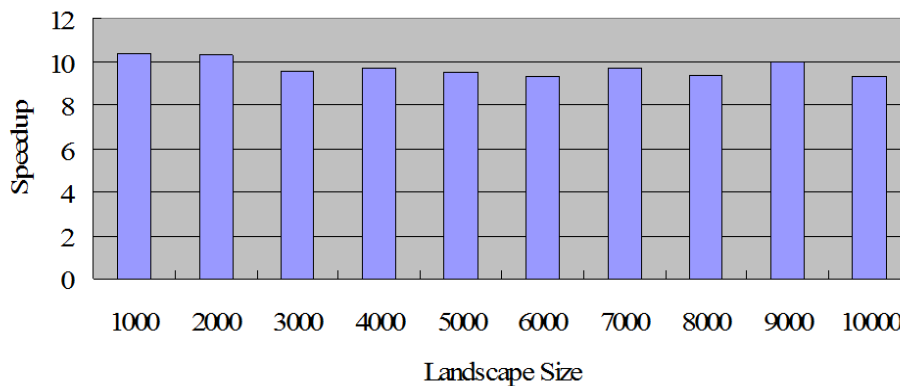


Figure 1. Parallel performance improvement for an agent-based model with different landscape size.

4. Conclusion

In this paper, we described the implementation of a parallel agent-based model of land-use opinion dynamics using the emerging GPU technology. We demonstrated the feasibility and utility of GPUs for parallel agent-based modelling using CUDA, representative of the state-of-the-art parallel computing platforms. Parallel algorithms that we developed enable the distribution of computation for agent-based interactions into computing cores in GPUs. The many-core architecture and high-performance computing capabilities of GPUs allow for computationally intensive agent-based modelling, even within desktop computing environments and at a relatively low cost. Our GPU-accelerated ABM leverages increasingly available GPU resources for parallel spatial simulation and, thus, potentially enhances our understanding of dynamics in CASS.

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