Geometric Algorithms in Geographic Information Systems

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The Challenge

Software applications that perform geometric computation—Geographic Information Systems (GIS), computer graphics, solid modeling, and scientific computation, to name just a few—are proliferating. Often they are doing so on geometrically-impoverished data structures. Our research into computational geometry seeks to answer the question, "How can the explicit representation of geometric structure enrich the set of operations in spatial data handling?"

To take a familiar example, consider spatial information on a map. In a GIS, a map is almost certainly represented either as:

(1) a raster,

(2) unorganized points and segments, or

(3) "topologically-structured data," encoding the connections of the points and line segments as a graph.

None of these structures says anything about the "space between the lines," which is perhaps the most obvious feature on a paper map. When we look at a map, however, we immediately look for answers to questions about areas, shapes, nearness, neighborhoods, groups, and clusters. For computers to participate in answering these questions (beyond simply displaying maps), they require algorithms and data structures that deal with these geometric concepts.

Dynamic spatial phenomena: Flood and fire in the Walnut Gulch Experimental Watershed

Highlights

Geographic Information Systems (GIS) are software packages used to create, to present, and, most importantly, to analyze maps. While many of the issues in GIS are common to databases and to heterogeneous systems, some of the key operations are essentially geometric. Examples that we investigate include:

a) Exact segment intersection and polygon overlay.

b) Building, storing, and transmitting triangulated terrains.

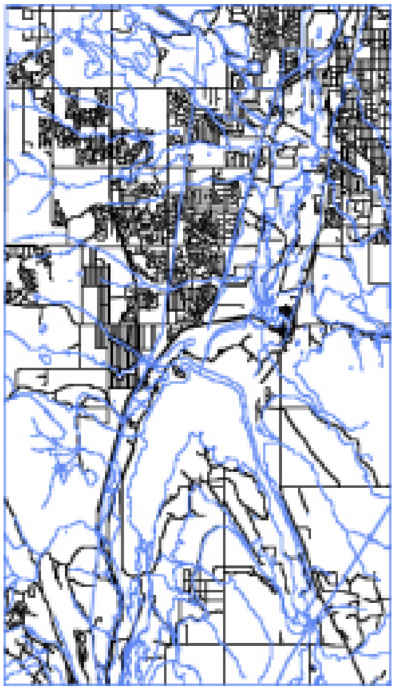
c) Dynamic data on terrain, especially simulation and display of water flow and fire propagation.

Our ability to represent, store, analyze, and visualize spatial data has significantly expanded over the last twenty years with the development of geographic information systems (GIS). However, existing GIS tools retain the temporally static nature of the models from the 1970's. They do not allow us, for example, to characterize a landscape, and the processes evolving on it, at a level of detail that is best suited to the dynamic requirements of the simulation.

The Approach

We sketch two example projects to illustrate geometric computations in GIS: robust polygon overlay, and dynamic data on terrain models.

The most basic operation in GIS processing is to overlay two maps to create a third. For example, to inventory all locations where bridge and culvert maintenance may be necessary, one could overlay a map of roads with a map of rivers in a region, then overlay a map of administrative districts to find out which districts are responsible for which locations. This simple operation of overlaying 2D maps is surprisingly difficult to compute robustly. One reason is the number of degenerate cases for of overlapping segments—a road or river may be an administrative boundary, but may be represented differently at a different scale. Another is that

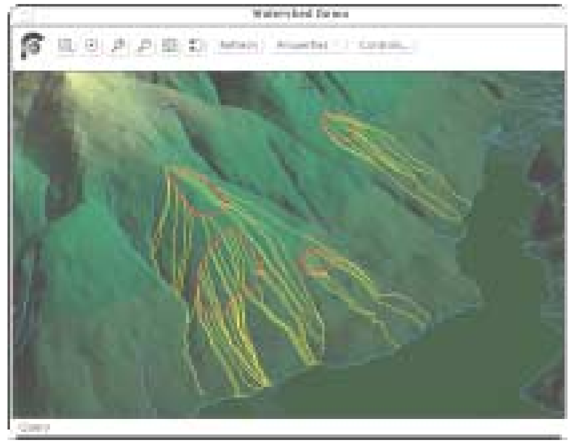


Overlaying roads and rivers

algorithms compute intermediate values and points that require higher precision than the input, resulting in arithmetic roundoff or overflow.

In one project, we have developed a new exact algorithm for building overlaying line segments that uses only double the input precision. (The classical Bentley-Ottmann line sweep requires quintuple precision!) To develop this algorithm, one thinks of line segments as being floppy curves, because one cannot test all of the properties of straight-line segments without using higher precision. Nevertheless, the result is quite simple, and we plan to demonstrate its practicality for large GIS data sets, for polygon clipping, and for boolean operations in CAD/CAM.

In our second project, we are extending terrain visualization systems (TVS) to simulate and display natural processes that involve dynamics across the entire terrain, and not just at isolated markers. We aim to support two example dynamic processes, surface water flow and fire propagation. Consider flow on a terrain after rainfall: Water will collect in channels, which grow as they roll down the landscape. Dynamic data describing this event can come from samples—in this case, rain gauges and flow gauges—or from simulation. Visualization can display this process directly, or can display the changing conditions of soil moisture content, which impact soil contamination, vehicle mobility, or flame propagation.



Runoff from potential forestry cut blocks

The goal of this project is to develop a system for multi-level adaptive simulations of natural processes, based on dynamic levels of detail in space and time. We will achieve this by applying advances in computational geometry, algorithms, and data structures to improve our ability to model, simulate, and visualize environmental systems. This will be done by dynamically representing the spatial variability and complexity of a landscape to meet simulation and visualization requirements. We propose to create an interactive system that can deal with large-scale tasks, such as those required for the simulation and visualization of rainfall-runoff or fire events. The availability of such a system will be of great use in a diverse set of applications such as natural resource management, flood and fire prediction, erosion protection, non point source (NPS) contaminant control, and urban planning.

We are at a crossroads—with recent advances in spatial data collection, storage, and analysis, coupled with advances from computer science in geometric algorithms, data structures, and visualization, we have the potential to better represent our landscapes at varying, nested resolutions, and to advance our ability to model natural phenomena.

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Key Words

Geographic Information Systems (GIS); computer cartography; digital terrain models; polygon overlay processing