Dynamic GIS

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Most GIS are an epitome of static, which is why to many people the word ‘dynamic GIS’ is an oxymoron. GIS usually is about data and to a much lesser degree about what can be done with the data. As such, GIS can be compared to early 20th century geography – an Aristotelian description of ‘where is what’ and ‘what is where’ (Barnes 1984). Process, and the notion of change, are acknowledged on the sidelines of GIScience research but have not yet become main stream in everyday GIS use. This is in spite of some 15 years since Tomlin’s ‘cartographic modeling’ (1990), the success of the GIS and Environmental Modeling conference series (Goodchild et al. 1996, Clarke and Parks 2001), and well-established pockets of spatial process modeling research such as Peter Burroughs group in Utrecht, NL. This chapter will reframe some of the work usually subsumed under the header of geocomputation by focusing on a single but new dimension - time - and uncovering low-level structural problems (Burrough 1992) that make it so hard to merge the spatial and temporal aspects of GIS data models.

Similar to the diversity of disciplinary origins of GISystems in the 1970s (US Census Bureau 1969, Tomlinson 1973, Dutton 1978), current approaches to dynamic GIS come from a variety of backgrounds. IT-related approaches are cellular automata and agent based modeling systems (Itami 1988, Clarke and Gaydos 1998), classical physical geography software development focuses on the marriage between traditional fluid dynamics modeling and GIS (Maidment 1993, Wesseling et al. 1996), civil engineers expand the realm of CAD by adding sophisticated schedulers (SCADA 1991, Miller and Shaw 2001, Zlatanova et al. 2003), and 2004 is the first year that a major vendor releases a scripting tool that allows end users rather than developers to create their own dynamic spatial models (ESRI 2003). So far, there have been few efforts to combine all these approaches and to give them a coherent scientific foundation. As such, this chapter is as much defining a GIScience research agenda as it is reporting on early successes of such research.

Among the earliest of such endeavors were quite appropriately a row of dissertations in the early 1990s that independently aimed to summarize different approaches to the incorporation of temporal elements into GIS analysis (Hazelton 1991, Kelmelis 1991, Al-Taha 1992, Langran 1992, Hamre 1994). Accompanied by academic prototypes, they all sought to add temporal querying capabilities to existing GIS structures. These temporal extensions to GIS have predominantly been modeled either as snapshots, where each layer represents an instance in time, or by amendments vectors, where each entity is associated with list that contains information regarding each change in the entity (Langran 1992; Peuquet 1994).

The “snapshot” data model, the earliest representations of time in GIS, organizes space over time, where each raster layer is used to represent a state of the world at a point in time (Wachowicz 1999). A collection of those spatio-temporal snapshots is used to represent a 4-

D space-time cube, where at each time step there is a tuple of object id, space, and time (Peuquet 2001). This snapshot model is conceptually intuitive, convenient, and easily adapts to available data sources such as satellite imagery, hence it remains prevalent due to its simplicity (e.g. Chen and Zaniolo 2000). Problems of large-scale data redundancy, where over time phenomena do not change everywhere, produced an alternative, the base-state with amendment model. This model updates states from the initially complete snapshot for only those objects that undergo change (Langran 1993). For both these approaches, change is interpolated, whether it be between system states or object states.

Incorporating time into the raster and vector data models is seen as the obvious solution to representing dynamics. However, as argued by Peuquet (1994), time and space exhibit important differences that do not comply with the neat addition of dimensions. Recognition that 'simply extending a spatial data model to include temporal data, or vice versa, will result in inflexible and inefficient representations for space-time data' has produced a slew of spatio-temporal alternatives (Peuquet 2001: 15). Alternatively, time can be represented by space, as has been developed in time geography, which implements Hägerstrand's classic model of temporal phenomena (Hägerstrand 1967). Computational implementations of time geography represent the potential path of an individual as a spatial extent which changes over time as the individual moves through space over time (Huisman 1998, Miller 2003a).

A different approach, first described by Kirby and Pazner (1990) and expanded by Smith et al. (1995), Pullar (2001, 2003) and Pedrosa et al (2002) is the idea to concatenate GIS procedures to modeling scripts. While these are add-ons to existing GIS structures, Wesseling, et al. (1996) went one step further with the integration of a full-fledged dynamic modeling language into their PCRaster system. Both ESRI's geoprocessing framework (ESRI 2003) and PCRaster's modeling language integration have proven the validity of their approach by being marketable. However, there are many limitations to this coupling of inherently discrete and continuous modeling approaches, which have been well documented (Waters 2002). As Kemp (1997a: 232) notes, "In order to fully integrate the two we need to add dynamics and continuity to our understanding of spatial data and spatial interaction and functionality to the environmental models".

Object-orientation has been hailed as a new basis for representing environmental processes (Raper and Livingstone 1995; Wachowicz 1999; Bian 2000). Object orientated approaches typically handle time by time-stamping objects or time-stamping their attributes (Stefanakis 2003). Yuan (1996, 2001) developed typologies of modeling change, where change is represented as a new state with a new time stamp. This expression draws apart the temporal, spatial, and attribute dimensions, reducing change to a variety of distinct forms. For capturing change in spatial objects, various temporal interpolation methods have been proposed for geometric changes of spatial objects (Zhang and Hunter 2000).

While all of the above mentioned work can be seen as a natural extension of GIS technology, other, usually more social science oriented researchers started to look at cellular automata (CA) and agent-based modeling (ABM) systems in an attempt to capture individual spatial behaviors. The far majority of CA-based research (Couclelis 1985, 1997, Batty and Xie 1994, Wu 1998, Batty et al. 1999, Shi and Pang 2000, O'Sullivan 2001, Benenson et al. 2002) uses this simulation environment to determine which spatial configurations and what set of rules (behavior) lead to a desired or observed urban form. University College of London's Centre for Advanced Spatial Analysis has been the source for an impressive array of software tools that mix and match CA and ABM to mimic urban landscapes. Similar to Batty's (1994) fractal cities, the emphasis is on prediction and the exploration of new techniques.

More theoretically oriented is the use of ABS by a group of European regional scientists (Bura et al. 1996, Nijkamp and Reggiani 1998, Sembolini 2000, Benenson and Torrens 2004), who seek to develop software environments that help to create explanatory spatio-temporal models. These models are formal specifications of conceptual models in settlement geography, regional economics, political geography, and in one rare case coastal geomorphology (Raper and Livingstone 1995, Raper et al 1999) and as such are aimed at confirming existing or developing new theories. This is in stark contrast to their U.S. counterparts (Smith et al. 1993, Westervelt and Hopkins 1999, Villa 2000, Agarwal et al 2001, Jenerette and Wu 2001, Gimblett 2002, Waddell 2002), who are very application-oriented.

These developments have lead to what has been termed dynamic GIS (De Vasconcelos *et al.* 2002). Here the lines between the traditional fields of GIS and computational simulation are rapidly blurring, with both the increasing integration of GIS data structures into computational simulation tools and the converse of the import of simulation tools into a GIS environment. For example, De Vasconcelos *et al.* (2002) present a dynamic GIS which is based on a "geounit", a CA like data structure which extends that simple formalism to any form of spatial structure and is combined with scheduled and event based events. A further example of the integration of computational simulation and GIS is the development of CA within a GIS, for example, van Deursen developed a spatially distributed hydrological model in PCRaster (an open source GIS developed at the University of Utrecht), which is essentially a CA (1995). ABM are also being coupled to GIS for importing spatial data (Gimblett 2002).

In either case, ABM systems do little to address the fundamental shortcomings of GIS (Chrisman 1987, Burrough 1992, Raper 2000). One of the first to basically start from scratch with the development of a new four-dimensional data model was Donna Peuquet (1992, 1994), whose work resulted in a series of research projects (MacEachren et al. 1999, Peuquet and Guo 2000) and sparked a new generation truly geographic (as opposed to computer science as discussed further down) data modeling literature (Yuan and Lin 1992, Peuquet and Wentz 1994, Peuquet and Duan 1995, Tryfona and Jensen 1999,Wachowicz 1999, Yuan 1999, Mennis et al. 2000, Renolen 2000).

Although the discipline of geography has adopted to notion of process almost 100 years ago, it failed almost completely to scrutinize the fundamental role of time. Non-computational exceptions were Blaut (1961) Hägerstrand (1967), Carlstein et al. (1978), and Pred (1981). Now, we experience a renaissance of 'time geography' and the works of Egenhofer and Golledge (1998), Kwan (1998), Frank et al (1999), Bian (2000), Raper (2000), Frihida et al (2002) and Pereira (2002) provide the first usable geographic conceptualizations that were compiled with an implementation on a computer in mind. The crucial difference to FORTRAN hacks of previous generations is that these are genuine geographic models and not mere adaptations of physics. Miller (Miller and Wentz 2002, Miller 2004 a, b) summarizes the current state of geographic conceptualizations of space and time.

The next step in implementing these new geographic models on a computer is to develop formal spatio-temporal specifications or ontologies. Starting with Casati et al. (1998), this has become a new hotbed of GIScience research (Hornsby and Egenhofer 2002, Mota et al 2002, Bittner and Smith 2003, Reitsma and Bittner 2003). Philosophers, computer scientists and geographers are now concentrating on two phenomena and their conceptualization, representation, and analysis (Erwig et al. 1999): one is the notion of 'process' (Claramunt and Thériault 1996, Chen and Molenaar 1998, Pang and Shi 2002) and the other that of 'change' (Frank et al. 1999, Galton 2000, Hornsby and Egenhofer 2000, Worboys 2001).

Traditional representations of geographic phenomena (Berry 1964, Goodchild 1990) are object centered, where an object has a location (x, y, z), some attributes (a, b, c), and rarely also some time stamp (t). This is usually represented as $G = f(x, y, z, [t], a, b, c, \ldots)$. The geographic object G can be one or more raster cells or some vector geometry, in which case a, b, c, t would be held constant over whatever area G covers.

Complementary to this object-centered perspective is a process-based one, where the primitive is a tuple of the form $(x_1, y_1, z_1, t_1, a_1, b_1, c_1, \Delta, x_2, y_2, z_2, t_2, a_2, b_2, c_2)$. Vector Δ represent some form of transformation, including the null transformation, where nothing changes, in which case $x_1 = x_2$, $a_1 = a_2$, etc. Process as primitive provides leverage for querying and analyzing processes. Crucial to the identity of a process is its pattern of change, vector Δ from above.

1. Example: Air Traffic Control

Ultimate goal of the whole ATC is to get airplanes safely from one place to another. Safely means that there should be a minimum amount of distance between planes, measured in minutes (between takeoffs) or miles (3 horizontal, 1000' vertical near the airport, 5 miles and 2000' vertical further away). The main process is the flight itself, a path determined by waypoints and time stamps. Both aircraft separation and flight plan are obviously easily represented in the tuple structure given above. This main process can be divided into eight subprocesses, which form the eight different classes of flight directives that an air traffic controller may communicate to the pilot (see figure 1).

Auxiliary processes the communication between air traffic controllers and management of up to 30 airplanes per individual controller; they are well codified (Wickens et al. 1998) and include all the contextual and relational information that we would place into our blackboard structure such as: the hierarchy of system command center, route traffic control centers, sectors, TRACONs and terminal air traffic control towers; the system of airspace classes, and especially the protocol for transferring responsibility from one controller to the next one along the flight path. This all works fairly well until bad weather or human error moves a complicated system into a state of complexity. Example 2 deals with the weather.

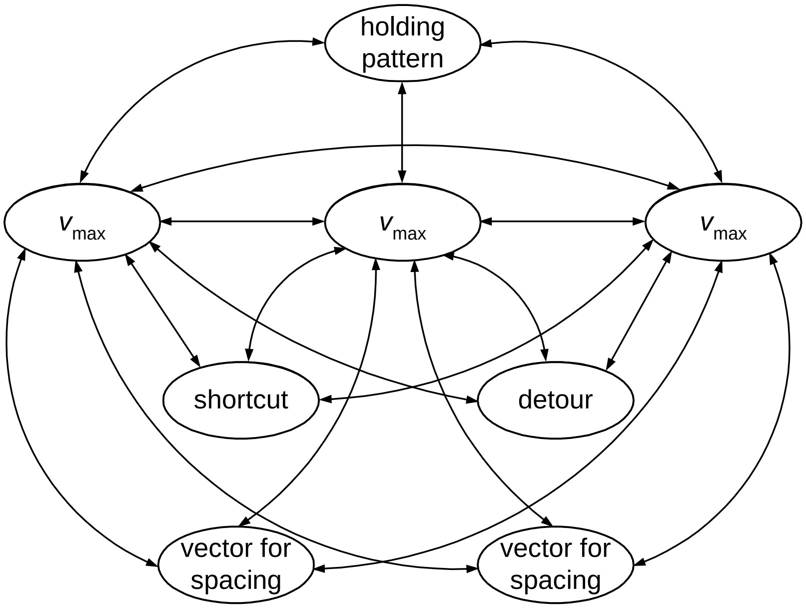

Figure 1. Eight possible ATC commands for a single aircraft (from Bayen et al. 2003).

2. Example: Advanced Regional Prediction System

ARPS is a development of the Center for Analysis and Prediction of Storms at the University of Oklahoma. The following description is extracted from their 700+ page user manual. A storm is the movement of air masses, the prediction of which is dependent on momentum, heat, mass, and water transfer, and turbulent kinetic energy. The model is essentially an equation of state that is initialized using prescribed analytical functions. The basic model variables are defined as :

$$u(x,y,z,t) = u(z) + u'(x,y,z,t)$$
$$v(x,y,z,t) = v(z) + v'(x,y,z,t)$$
$$w(x,y,z,t) = w'(x,y,z,t)$$
$$\theta(x,y,z,t) = \theta(z) + \theta'(x,y,z,t)$$
$$p(x,y,z,t) = p(z) + p'(x,y,z,t)$$
$$\rho(x,y,z,t) = \rho(z) + \rho'(x,y,z,t)$$
$$q\mathrm{v}(x,y,z,t) = qv(z) + q\mathrm{v}'(x,y,z,t)$$
$$qli(x,y,z,t) = qli'(x,y,z,t)$$

where u, v and w are the Cartesian components of velocity (momentum), θ the potential temperature, p the pressure, ρ the density, $q\mathrm{v}$ the water vapor mixing ratio, and qli one of the hydrometeor categories. The over-barred variables represent the base state and the primed variables are the deviations.

ARPS solves prognostic equations for u, v, w, θ', p' and $q\ \psi$, which are, respectively, the x, y and z components of the Cartesian velocity, the perturbation potential temperature and perturbation pressure, and the six categories of water substance (water vapor, cloud water, rainwater, cloud ice, snow, and hail). The whole ARPS model is hence one huge tuple of the form $(x_1, y_1, z_1, t_1, a_1, b_1, c_1, \Delta, x_2, y_2, z_2, t_2, a_2, b_2, c_2)$.

The challenge (and opportunity) in linking the air traffic control model with the storm prediction model is to determine when what characteristic of Δ of the ARPS model is likely to have a negative impact on Δ in the ATC model.

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