# REPRESENTATION AND COMPUTATION OF GEOGRAPHIC DYNAMICS

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Any discussion of geographic dynamics must first and foremost be based on a clear definition of domain – what do we mean by geographic dynamics, what is included, and what is excluded? Geography is often defined as the study of Earth as the home of humanity, and this definition provides a basis for limiting geographic dynamics to those time-dependent aspects of the human environment that affect and are influenced by human activity. The geographic domain is the Earth's surface, and needs to include those parts of the subsurface and atmosphere that interact strongly with the surface – say from 10km above to 1km below the surface, which is sufficient to include most aspects of weather and groundwater. For the most part the concern is with the present, though predictions of future states will be important in so far as they impact human activity, and the past will be similarly important in some applications. The focus on human interaction can also provide the basis for delimiting the domain in terms of spatial and temporal resolution. At the far end of the scale, there will likely be little interest in processes with spatial resolutions coarser than 10km or temporal resolutions coarser than days. It is more difficult to speculate about the near end of the scale, particularly in the context of dynamics relevant to intelligence, so for the purposes of argument let us take 1cm and 1sec as the limits, giving a range of 6 orders of magnitude in space and 5 in time.

This is an enormous domain, covering applications as diverse as mesoscale atmospheric modeling, tidal and storm-surge modeling, models of human spatial behavior, models of the foraging behavior of elephants, and models of land-use transition. Only some of these are traditionally studied in the discipline of geography, since numerical modeling in the geographic domain is now common in disciplines ranging from geophysics and ecology to civil engineering and economics. Only GIScience, however, seems sufficiently broadly based to take on the challenging task of finding commonalities and gaps, and of designing general-purpose representations and computational systems that can address the needs of the entire domain.

Traditionally, geographers and others have distinguished between *form*, which can be defined as the state of the system; and *process*, the set of rules, equations, algorithms, and codes that represent the transitions of the system through time. Form has often been regarded as static or cross-sectional, representing the state of the system at time $t$, but in the context of this discussion it is important to recognize that form can be spatio-temporal, tracking the system through time. In this framework much of science is about reasoning from spatio-temporal form to process, on the grounds that process can leave an identifying footprint on form. It is often argued that knowledge of process is more valuable than knowledge of form, since process knowledge is abstracted from space and time, whereas form knowledge is simply descriptive. In this sense the form/process

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debate mirrors the wider *idiographic*/*nomothetic* debate in science. The distinction is also mirrored in the architecture of GIS, which assigns form knowledge to the database and process knowledge to the software.

In this framework the representation problem in geographic dynamics has two clearly differentiated parts: the database or form part, which must find efficient representations of the state of the system through time, and the software or process part, which must similarly find efficient representation of the rules and equations that define process.

It seems helpful at this point to introduce the field/object dichotomy, which structures much of our current understanding of the representation of form, and also provides a useful framework for the discussion of process. Many processes are conceptualized as operations on fields, and formalized as partial differential equations (PDEs). They include the Darcy equation of phreatic groundwater flow; the Navier-Stokes equation of the motion of viscous fluids, with applications in hydrology and atmospheric science; and equations describing the development of slopes in geomorphology. PDEs are solved using finite-difference (FD) or finite-element (FE) methods, the former corresponding to raster operations in GIS, though there is comparatively little implementation of FE methods on GIS platforms, and FE data models are not standard in GIS. Some PDEs are solved in the harmonic domain through operations on Fourier transforms, and these lie entirely outside the normal domain of GIScience (some global climate models are implemented in spherical harmonics). Other processes conceptualized as fields include land-use transitions, which have been implemented as cellular automata (CAs) with complex rule sets.

Other processes are conceptualized as operations on discrete objects, or on discrete objects moving within fields. They include many models of human and animal behavior, in which individuals or groups are modeled as autonomous interacting agents under rules that include object-to-object interactions as well as object-in-field interactions.

Within this framework it is possible to organize what is known about the representation and computation of geographic dynamics, to ask what still needs to be done, and to identify remaining issues. There are enormous economies of scale in systems that can provide support for the full range of applications, but the design of such systems is clearly difficult, since it must rely on and synthesize a vast array of use cases. But the benefits lie in reusable code, in programming languages whose level of granularity matches that of problem definition, in the ability to work in a single environment that spans the entire domain, and in easy translation of concept to implementation.

On the process side, the Utrecht group's PCRaster represents a broadly based attempt to design a common scripting language for processes defined on fields. Its raster basis limits its applications to processes defined through CAs and the FD approach to PDEs, so a broader effort to define a process-representation language that exploits the full range of field representations, including FEs, would likely produce useful results. While there has been some work on identifying the common components of a range of process models, there is as yet no equivalent of PCRaster for models based on objects or object-field interaction.

Representations of form, or data models, must anticipate both a broad range of use cases, and exploit what is known about geographic information in general. Tobler's First Law, for example, provides a very broad basis for the design of data models, and spatial heterogeneity has also been advanced as a general property of geographic information. We need similar principles for spatio-temporal form that can guide the design of data models. What, for example, is the spatio-temporal equivalent of Tobler's First Law, and what does it imply about appropriate data models, compression schemes, and indexing? Are the properties exploited by mpeg generally true of geographic information, or is an entirely different approach needed? To date, systems such as PCRaster that are designed for general-purpose modeling of geographic dynamics use very simple data models that surely fail to take advantage of general properties.