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Cellular Automata

Cover page

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Synopsis

Cellular automata have a very distinguished history, dating to the origins of the digital computing that now permeates our world ubiquitously. Cellular automata are the foundation of all computing media and are used throughout the physical, computer, and social sciences and mathematics. Their use in the geographical sciences dates to the 1970s, when they were employed in dynamic, raster-based, modeling of urbanization and later as abstract media for modeling pedestrian movement along streetscapes. Since the early-1990s, there has been an upsurge in their use and they are now employed in

modeling a diverse range of human and physical geographic phenomena. This popularity stems largely from the simplicity of their conceptual design as well as their natural affinity with spatial systems that rely on proximity, distance and distance-decay, adjacency, spatial composition and configuration, and diffusion as essential ingredients. Mechanically, cellular automata share mathematical and algorithmic structures with remote sensing, digital geographic data stored in rasters, pixels, and voxels, as well as low-level computing, Geographic Information Systems, object-oriented programming, and relational databases, which makes them somewhat of a natural fit for software engineering and geocomputation. Tools for building geographical models based on cellular automata are also widely available. Indeed, several options exist for building cellular automata within commercial and open source Geographic Information Systems.

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Introduction

Application of cellular automata to the study of geographical phenomena dates to the late-1960s and development of land-use change models by Chapin and Weiss. While famous today for the invocation of Tobler’s First Law, a short paper on urban growth modeling by Waldo Tobler in 1970 is among the earliest examples of geographers’ use of cellular automata. This work, while pioneering, was largely ignored by geographers for several decades, until interest was revived by Helen Couclelis in the mid-1980s, presaging a flurry of activity in the early-1990s and the emergence of automata modeling as a popular avenue of research inquiry thereafter.

The use of cellular automata in geographic research is illustrative of a broader paradigm shift in the social and life sciences, away from modeling using aggregated views of space and time and toward treatment of phenomena and systems as collectives of massive amounts of individual, independent, and heterogeneous entities; each represented at their own atomic spatial and temporal scale; connected and interacting dynamically in a complex adaptive fashion. In geography, this work draws inspiration from related research in sociology, economics, ecology, political science, physics, biology, chemistry, mathematics, and computer science. However, work by geographers is starting to have a reciprocal influence in these fields, infusing spatial thinking (and Geographic Information Science in particular) into the social and physical sciences.

Cellular automata: a primer

Automata are, fundamentally, computing media. Their origins date to Turing’s work on computable numbers in the 1930s. Examples from the computer sciences include finite state machines, Turing machines, and artificial neural networks. These basic computing automata may be characterized as follows:

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$$A \sim (S,R);\ S = \{S^1,S^2,\ldots,S^k\};\ R: (S_t,I_t)\rightarrow S_{t+1}$$

Above, A represents an automaton, characterized by states S and a transition rule T. The transition rule functions to manage changes in states S from time t to time t+1, given input of other state information from outside the automaton at time t. The transition rule becomes the medium of exchange, and states become the raw material, when many such automata are designed to co-interact. Automata of this form resemble Markov models (which deal with serial autocorrelation in temporal transition) and raster models (which deal with layering of state-space).

The cellular automaton adds an additional characteristic to Turing’s automaton or finite state machines: the notion that automata should be considered as being housed discretely within the confines of a cellular unit. The idea for the cellular automaton comes from Stanislaw Ulam and John von Neumann, following their work during the early foundations of digital computing in the 1950s.

Cellular automata are characterized as follows. Cells dictate the discrete (spatial) confines of the automaton. A lattice is an arrangement of neighboring cells to make up a global geographic space. Neighborhoods are localized areas of spatially-related cells around a given automaton, from which it draws input in the form of their state information. The neighborhood includes the target cell itself by convention. Transition rules are the processing engines for cellular automata, and may be designed in an almost limitless fashion. In fact, cellular automata are capable of supporting universal computation. Rules may be formulated as functions, operators, mappings, expressions, or any mechanism that describes how an automaton should react to input. Time is the final component of cellular automata and it is introduced as discrete packets of change in which an automaton receives input, consults its rules and its own state information, and changes states accordingly.

Adding cells to the basic automaton structure yields the following specification.

$$CA \sim (S,T,N);\ S = \{S^1,S^2,\ldots,S^k);\ R: (S_t,N_t)\rightarrow S_{t+1}$$

This looks complicated, but it is really quite straightforward. Above, CA refers to a cellular automaton, characterized by states S, a transition rule (or vector of rules) R, and a neighborhood N.

Various properties of geographic phenomena and systems may be mapped to these characteristics. Cells can be used to represent an almost limitless range of geographic “things”, from cars and land parcels to ecosystem ranges and microorganisms. Cells can take on any geographic form and this might be regular (squares, hexagons, triangles and so forth) or irregular. The boundary can convey information of direct geographic significance, such as the edges of property ownership, the footprint of a vehicle, or outer walls of a microorganism. Cells relate to the spatial boundary of an entity. Neighborhoods are used to represent the spatial (and temporal) boundary of processes that influence those entities: the community within which a property resides, the journey-to-work for a vehicle, or the range of chemotaxis for a microorganism. States are used to ascribe attributes to cellular entities: a parcel’s land-use, a car’s velocity, preferred glyconutrient for a human cell. Moreover, the states can be tied directly to phenomena that act within and/or on the cell and the larger system that it exists within. This is achieved using transition rules.

Transition rules tie all of these components together; they are the glue that binds cells, states, and neighborhoods. Cellular automata, like all automata, are universal computers. Given enough time, resources, and the right rule-set, they should be capable of supporting any computable statement. This lends terrific power to the transition rule. Cellular automata should, in theory, be able to simulate virtually *anything*. This stands in stark contrast to more traditional modeling methodologies available to geographers, which often limit the range of questions that can be answered with the tool. A gravity model, for example, can only support interaction expressed in terms of aggregate flows. Derivation of transition rules is key to use of cellular automata in geographic research. Transition rules are inherently tied to space-time as well as pattern and process. The rules can, therefore, be used to represent fundamental processes from Geographic Information Science, spatial analysis, and quantitative geography: spatial interaction, space-time diffusion, distance-decay and distance-attenuation, centrifugal action, centripetal action, and so forth.

The advantages of cellular automata modeling in the geographic sciences

Cellular automata have many advantages for geographic modeling. They are capable of supporting very large parameter spaces for simulation. A one-dimensional CA with a binary state set and 13 cells has 2^{13} possible configurations. A two-dimensional version of the same CA has 2^{169} possible configurations, and a three-dimensional CA with the same specification has 2^{2197}! If we were to divide the world’s land mass into 1 km^2 rasters and run a two-dimensional CA over it with 50 states (this is not unlikely, for example, if we were to develop a simple global climate model), the space of possible state-switches would be $25^{260,173,445,184,000,000}$. This is a *large* number.

The representation of space and time in cellular automata lends an inherent spatiality to the concept. Traditional modeling techniques in geography abstract from spatial detail. Cellular automata, on the other hand, make an implicit use of space and spatial complexity. Cells, neighborhoods, and lattices are inherently spatial. In addition, cellular automata are capable of supporting separate notions of space and time, as well as combined space-time relationships. The basic cellular concept also has a natural affinity with raster-based data structures common to Geographic Information Systems and image processing in remote sensing. The stratification of state variables in cellular automata is also synonymous with raster-layering in Geographic Information Systems. Similarly, the serial treatment of temporal relationships allows for the introduction of a formal hierarchy to dynamics that compliments Markov-like processes already popular in geographic modeling. Moreover, cellular automata are capable of representing form and function, pattern and process.

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Cellular automata and complexity

Cellular automata have further advantages stemming from their relationship with complex adaptive systems. Complexity studies focus on the grassroots of system dynamics, emphasizing the local interaction among elements that give rise to phenomena at synoptic scales. In modeling, the complexity approach also focuses on issues such as the importance of historical (seed) conditions, feedback between subsystems, interaction, dynamics, phase transition, noise and perturbations, and so forth. Cellular automata are among the best and most widely-used tools for complexity modeling.

Human geography applications

Cellular automata have been employed in the study a wide range of geographic phenomena. The plethora of applications is illustrative of the usefulness of the approach. Human geography applications are largely focused on issues relating to urban geography and behavioral geography.

Models of urbanization and urban growth feature prominently in the literature. Cells are generally used to represent areas of urbanization or land parcels, with cell boundaries matched to pixels in remotely-sensed images. States can be relatively simple, with binaries representing urbanization, for example. State specification can, however, be much richer, formulated as layers of land-use or activity (synonymous with attribute layering in a Geographic Information System), or as fuzzy membership. A variety of transition rules have been employed as representative of the forces of urbanization. These include urbanization based on agglomeration through diffusion-limited aggregation; land-use transition based on potential for development; physics-driven mechanics; data-driven rules from statistical analysis; data-trained rule-sets from artificial neural-networks; and spatial heuristics. In some cases, different rule-sets are employed as what-if experiments to test the varying influence of urbanization processes. In this sense, cellular automata are used as artificial laboratories to test theory, as tools to think with.

Cellular automata have also been used to model other aspects of human geography. Work by Schelling and Sakoda with simple chessboard models is among the early antecedents of cellular automata simulations of socio-spatial segregation. Cells are equipped with states that correspond to ethnicities, and rules based on preferences for co-location in space are used to show how small biases can quickly lead to large-scale segregation from random initial conditions, and to investigate the tipping-point at which socio-spatial segregation begins. More recent models of residential mobility follow similar schemes, with rules designed to introduce more elaborate mechanisms based on spatial choice and dissonance.

David O’Sullivan has also developed a model of gentrification dynamics based on cellular automata. Cells are used to represent gentrifiable real estate and rules are introduced to test rent-gap hypotheses from the theoretical literature.

Automata-based work on traffic simulation is largely agent-based, but several applications have been developed using cellular automata. Cells are used to represent vehicles and pedestrians in these instances, with movement formulated by proxy using transition rules that pass the presence of these entities as state information between cells based on heuristics designed to mimic lane-changing, collision avoidance, stopping, queuing, and junction navigation.

Physical geography applications

Cellular automata models are also popular in physical geography research. Global climate models and general circulation models in climate and meteorology studies function, at a global, level as cellular automata. At a macro-level, GCMs are divided into large cellular grids composed of cells of around one degree of latitude and longitude in size. Various models simulate the internal climatic dynamics within these cells, but the results are generally exchanged through the larger grid on simple cellular automata schemes. Cellular automata are very efficient tools for representing processes of geomorphological transport and feature as the geographic engine in models of particle movement. Diffusion-based rules have been used for these purposes in models debris flow. Cellular automata are used in a similar fashion, as the mechanism of mobilization in models of wind transport for snow movement and dune formation, for example. Transition rules are naturally accommodating of calculus-based equations in these applications.

Cellular automata are crucial to the design and application of fire models in physical geography work. Some of the most advanced computational work with cellular automata has been realized in development of wildfire simulations.

Geographic applications in other sciences

Cellular automata have also been used in a variety of social science applications outside the geographic sciences, largely due to their value in representing geography in simulation. Cellular automata with fundamental space-time representations have been used in anthropology, to model the formation of societies and in political science and sociology to explore civil violence. Cellular automata have been particularly useful in infusing geography into work in economics. Models developed by urban economists, for example, rely heavily on cellular automata to represent processes of urban agglomeration. Cellular automata models that are fundamentally geographic in inspiration have also been widely used in ecology to simulate floral and faunal dynamics and in biology, where they are employed in the modeling of cellular dynamics and tumor formation.

The future for cellular automata in geographic research

Research work in this area is focused on a broad range of interests. Development of new applications is still quite active, with new cellular automata models popping-up for a variety of phenomena of geographic interests, with an associated growth in their use as test-beds for theory, practice, and policy.

Researchers have also begun to focus on extending the basic idea of cellular automata from mathematics and computer science for geographic applications. Work in specifying cells, lattices, and neighborhoods through Geographic Information Systems is particularly active, with recent advances in the use of graphs, Voronoi polygons, irregular cells, and 2.5 D lattices.

Cellular automata are naturally allied with remote sensing, Geographic Information Systems, and the dataware associated with them. Various attempts have been made to develop cellular automata engines within Geographic Information Systems and to build GI Systems functionality into cellular automata. Recent work, however, has focused on the mutual links between cellular automata and Geographic Information *Science*.

Research into the connections between cellular automata and agent automata is central to the current research agenda. The two are popularly confused, even though the distinction on geographic grounds is reasonably straightforward: cells don't actually move within their lattices and engage in action-by-proximity, while agents can move freely in vector spaces and can engage in action-at-a-distance. Tool-kits and methodologies are just beginning to be built that support both approaches.

Issues surrounding calibration and validation of cellular automata models are chief among challenges facing future research in this area. Existing work has an over-arching focus on patterns and their role in benchmarking cellular automata models, but research into the role of processes in validation and calibration is comparatively under-developed.

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