Application of 2-color 1-dimension range-2 cellular automaton for dynamic change of shading panel opacity

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Abstract
Paper presents creative use of cellular automata (CA) in architecture, namely for dynamic shading of building facade. The abbreviation “CA” refers both to singular form “cellular automaton” and plural- “automata”. One of the most interesting "visual" quality of CA is abilty to create organic patterns which sometimes are very pleasing to human eye. These patterns seem to "live their own life" and "taming" them to perform purposeful actions is quiet challenging due to their computational irreducibility as shown in an example of possible practical application, but as a result, provides visual effects of unmatched intriguing complexity hard to achieve by means of artistic will, whim or chance. Although amazing qualities of CA astonish for many years, their practical (physical) applications are still very sparse if existing at all, besides "pretty pictures". Four classes of CA "behavior" with conjunction to the problem of "pattern average grayness" was presented. Two classes of CA were analyzed: 2- color, 1- dimension, range- 1 (2C-1D-R1) and 2-color, 1- dimension, range- 2 (2C-1D-R2) for potential practical use. Problem of monotonic gradual change of average grayness as a function of sequence of initial conditions was discussed. Scheme of mechanical system realizing the idea of shading controlled by CA was proposed.

1 INTRODUCTION

A cellular automaton is a collection of "colored" cells on a grid of specified shape that evolves through a number of discrete time steps according to a set of rules based on the states of neighboring cells. The rules are then applied iteratively for as many time steps as desired. In the 1940's, Stanislaw Ulam, while working at the Los Alamos National Laboratory, studied the growth of crystals, using a simple lattice network as his model. John von Neumann was one of the first people to consider such a model, and incorporated a cellular model into his "universal constructor". John von Neumann's Universal Constructor is a project of a self-replicating machine in a 29 states cellular automata environment. It was designed in the 1940s, without the use of a computer. Even though cellular automata can in general be executed extremely rapidly, the enormous size of the “tape” required to fully describe the self-replicating cellular automaton has never been demonstrated. Due to increase of computational power of computer simulators, although the “machine” is still of merely theoretical and historical interest, it is expected to soon be of practical value in the study of evolutionary processes. Further, the flexibility of the von Neumann model suggests that it will also prove valuable for the study of fundamental biological processes, such as epigenesis and embryology. Cellular automata were studied in the early 1950s as a possible model for biological systems. Cellular automaton can therefore be viewed as the simplest model of life and as such, often despite its striking simplicity produces puzzling results. In a nutshell, these are the only requisites of CA: regular grid, set of rules and initial state.

The combination of these three elements result in so called “behavior” of a cellular automaton.

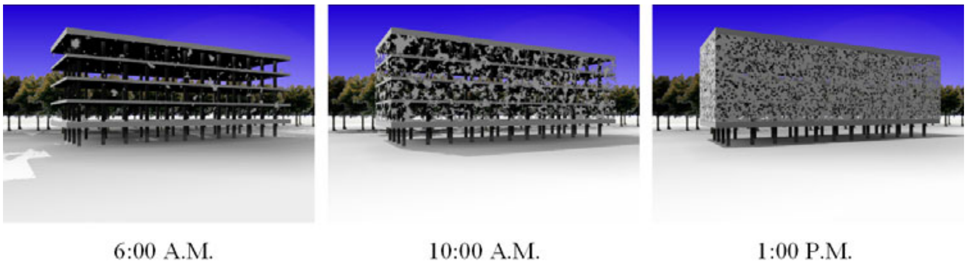


Figure 1. Visualization showing “organic behavior” of building facade which opacity is controlled in way which responds to changes of daylight conditions

2 FROM SIMPLE TO COMPLEX

There are four main classes of CA behavior: constant, repetitive (and nested), (pseudo) random and complex. All these classes are already present in the simplest, non-trivial case- 2C-1D-R1 CA. Explanation of the naming convention: two color (2C = binary i.e. possible states of a cell are black- 1, or white- 0), one dimension (1D CA is a simple one-unit-high stripe of cells where state of cells changes in every cycle; it is convenient to show the history of changing states as a series of stripes together as an array), range-one (R1: a cell's neighbors defined to be the adjacent cells on either side of it, in other words a cell and its two neighbors form a neighborhood of 3 cells), “general” (where values of neighboring cells are input as oppose to “totalistic” where input is an *average* value of neighboring cells; the simplest general CA are referred as “elementary”).

3 GENERAL APPROACH

White (value 0) cell is equivalent to transparency of an facade element, similarly black (value 1) cell represents an opaque state. The ratio between the number of black (value 1) cells to all cells in the array is called “average gray”. For practicality, the gray-control over the CA array was assumed by the means of one edge of rectangular array, which therefore is an initial condition for CA while the rest of the array is a collection of rows (or columns) representing the CA's history of evolution. In further examples the very top row as the “controlling edge” and non-toric grid were assumed. Usually, to avoid problems at the edges of the grid, toric geometry is used, so e.g. the very right column is connected immediately to the very left column of the grid. In order to avoid “confusion” e.g. changes of state on the right size of array caused by configurations on the left side, a non-toric geometry was applied.

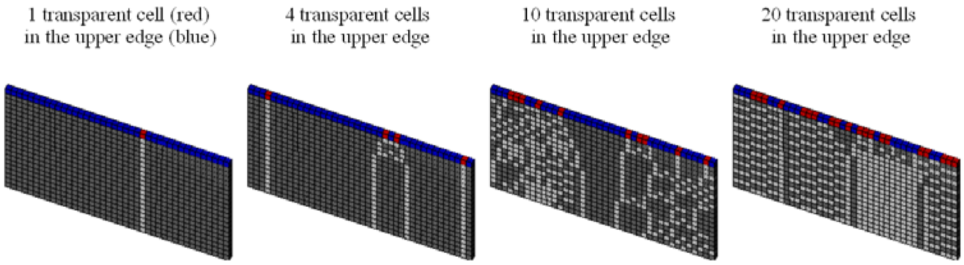


Figure 2. The overall grayness of the array is controlled by the top row. Four different initial conditions

4 2- COLOR 1-DIMENSION RANGE-1 ELEMENTARY CELLULAR AUTOMATA (2C-1D-R1 CA)

The search for appropriate CA started from the simplest non-trivial class: 2C-1D-R1 CA. There are 2^3=8 possible patterns for a neighborhood. There are then 28 = 256 possible rules- not too many. The search for interesting ones can be done by simple simulation. Table below shows the most appropriate ones i.e. the ones in which the function between the percentage of black cells at given initial conditions (initial gray) and total number of black cells of the created pattern (array gray) is fairly monotonic.

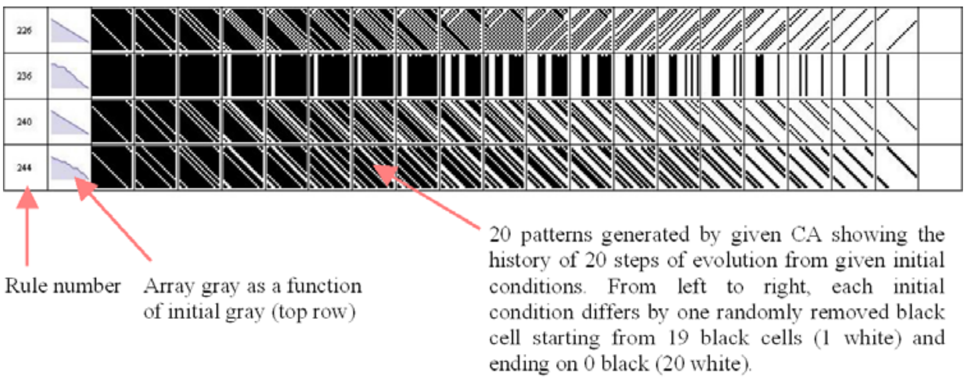


Figure 3. All 1-D CA that have (fairly) monotonic grayness function

The selection from all 256 CA was done by comparing the graphs of the gray function. Some observations where made:

- In the set of rules of the selected CA, the number of black cells usually equals the number of white cells with deviation of maximum 1. Below is the list of CA with corresponding number of black cells in their set of rules:

{142, **4**}, {154, **4**}, {162, 3}, {166, **4**}, {170, **4**}, {174, 5}, {176, 3}, {180, **4**}, {184, **4**}, {200, 3}, {204, **4**}, {208, 3}, {210, **4**}, {212, **4**}, {226, **4**}, {236, 5}, {240, **4**}, {244, 5}.

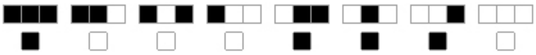


Figure 4. Example: {142, 4}= Rule 142 and 4 black cells in the set of rules

- At given set of initial conditions, if the number of black cells is 4, the gray function if fairly linear. If the number of black cells in the set of rules is lower (=3) or higher (=5), in general the curve becomes concave or convex respectively.

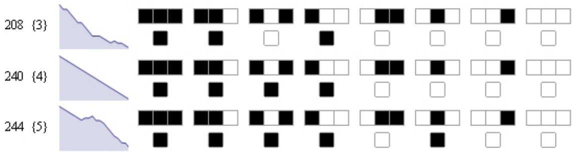


Figure 5. Convex or concave Grayness function depending on the proportion of black to white cells in the set of rules

All these CA have good gray-control, but they do not represent the most interesting class of behavior, namely Class 4 (Complex), therefore they are not the most interesting visually.

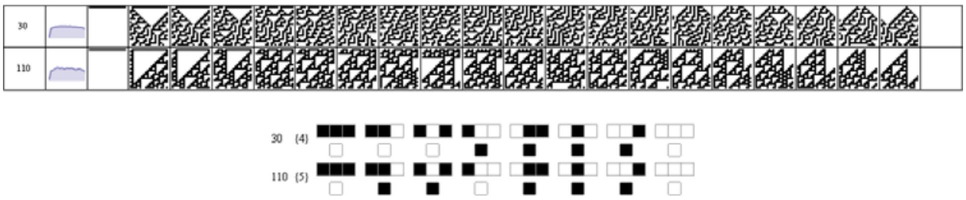


Figure 6. In the set of CA 2C-1D-R1 there are only 2 CA of Class 4, but the gray curve is non-monotonic

Perhaps it is possible to set the sequence of initial conditions even for those complex-behaving CA in a way that the overall gray of the whole array would gradually change, but the purpose of the project was to find CA that is both *easily* controllable and interesting. The next step therefore was to look at more complex class of CA.

5. 2- COLOR 1-DIMENSION RANGE-2 GENERAL CELLULAR AUTOMATA 2C-1D-R2 CA

The difference form the previous class of CA is the size neighborhood. Range-2 (R2) means that the cell's state is a function of the state of the two closest neighboring cells *and* two second closest cells on each side.

Figure 7. Sample set of rules (CA 2029576417= 111100011111100011100000111000012)

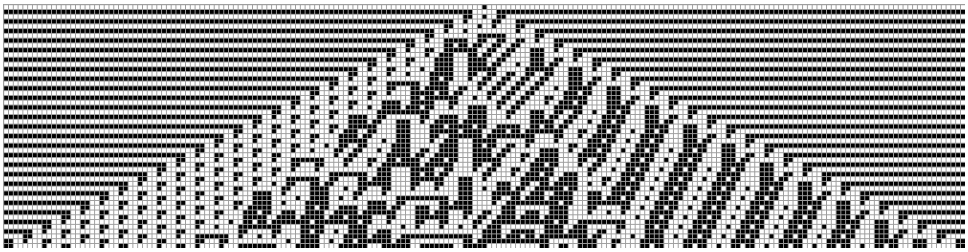


Figure 8. 50 step history of evolution of CA 2029576417 starting from a single black cell

Since there are 5 binary neighbor cells, there are $2^5=32$ possible patterns for a neighborhood. There are then 2^{32} = 4 294 967 296 possible rules. This is substantially greater number, therefore other search methods were used, namely based on rule *symmetry* so the patterns generated at k% of black cells at given initial conditions will be the same (but reversed) at k% of white cells. Below, there is an example where two R2 CA produce interesting geometrical patterns but only one is symmetric.

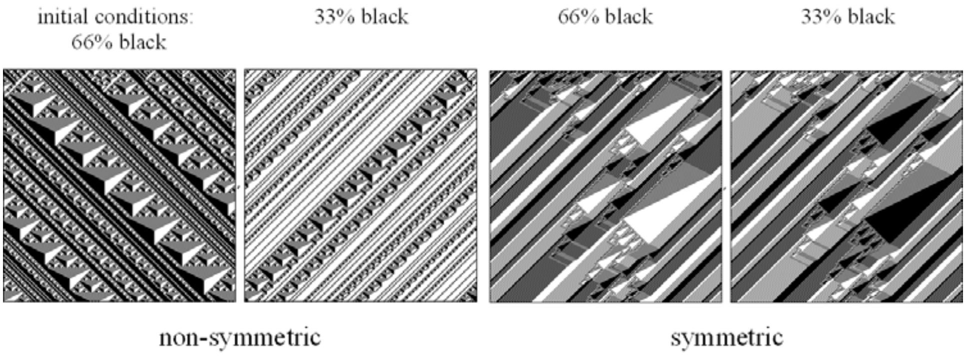


Figure 9. Comparison between non-symmetric and symmetric R2 CA.

Search was limited to rules which have 50% black and 50% white cells. There are $32!/(16!)^2$ = 601080390 such rules, which is approximately 14% of all the 2C-1D-R2 general CA rules.

Most of these rules however produce behavior that is neither interesting (dull patterns) nor useful (non-monotonic gray function).

Figure 10. Example of 2C-1D-R2 general CA rules shown with corresponding gray function at the same random sequence of initial conditions

Next step was to search through all those rules looking for ones that produce wide range of grays at fairly monotonic gray function.

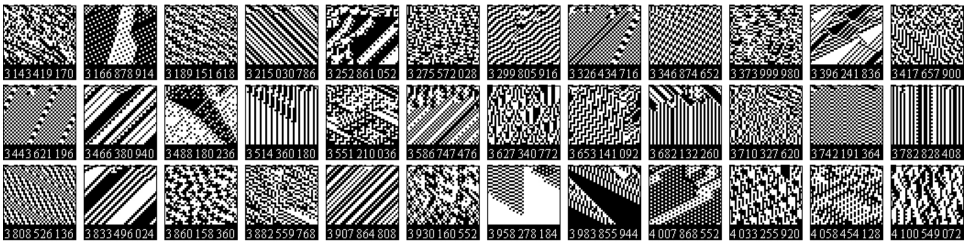


Figure 11. Some promising 2C-1D-R2 general CA with sample patterns

6. 2C-1D-R2 CA 3818817080

Finally rule 13818817080 were chosen. It produces highly attractive patterns although the control over the grayness function is problematic.

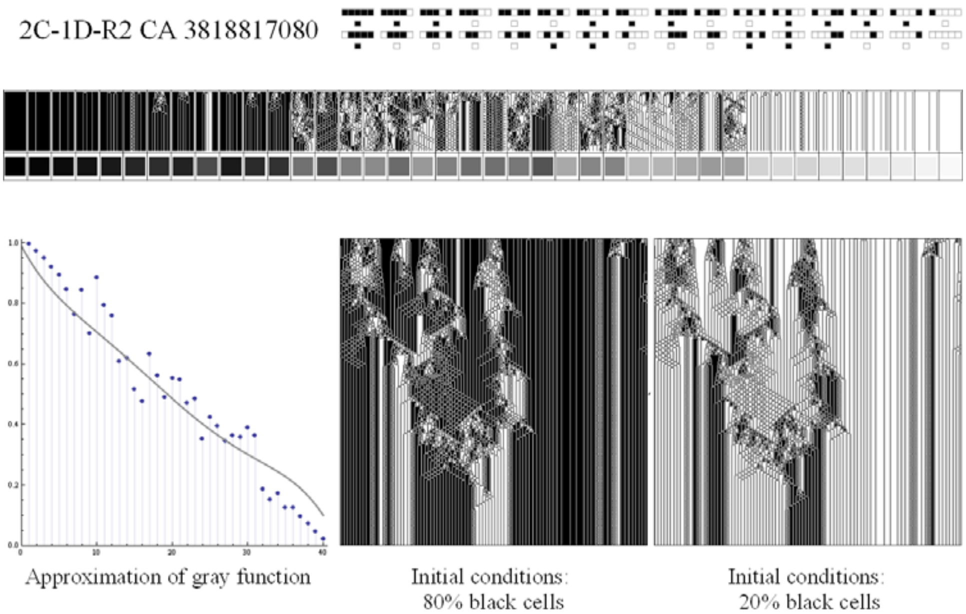


Figure 12. Rule 3818817080, set of rules, sample change from 100% to 5% black cells in the initial conditions, grayness curve and two symmetric sample patterns

7. INITIAL CONDITIONS

Setting the initial conditions is equally important as finding the appropriate rule. Lets consider 5-cell array. At the beginning, there are 5 black cells in the top row (initial cells). In the following example black cells turn white in 6 steps at following order: {1,2,3,4,5}. The change from black to white can be done in 5! = 120 different sequences.

Figure 13. Sample sequences of initial conditions for 5 cells

This simple example shows that some sequences of initial conditions give monotonic and smooth transition (e.g.{1,5,4,3,2} marked with green square) from black to white and some give very coarse non-monotonic transition (e.g. {2,5,4,1,3} marked with red square).

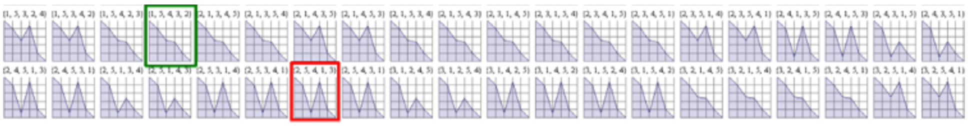


Figure 14. Gray curves of 5x5-cell array for 6 steps (from 5 black to 5 white cells) of 2C-1D-R2 CA 3818817080 corresponding to the figure 18

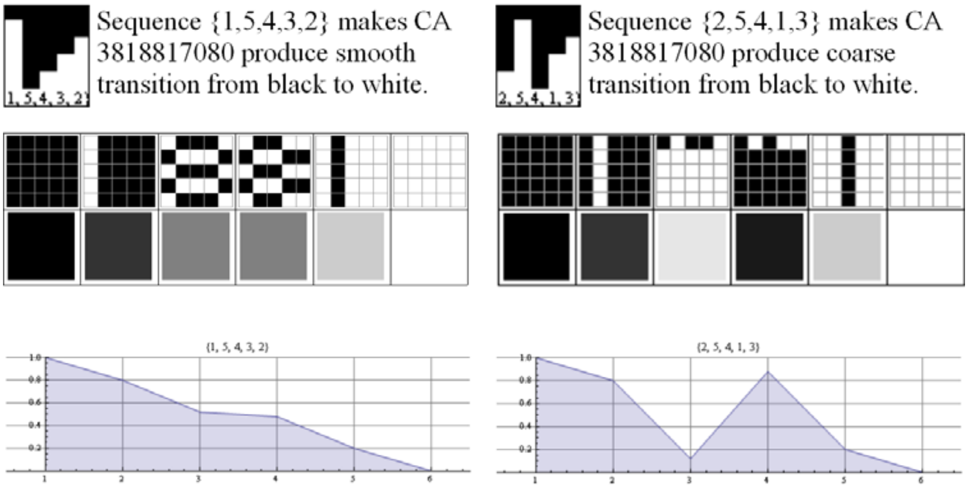


Figure 15. Transitions of states for two sequences of initial conditions marked on figure 22 with corresponding average grays

For moderate size of an array (in the range of a few dozens of cells), backtracking search method was used. In the case of larger (practical) sizes of array, the number of possible sequences of initial conditions grows astronomically, therefore heuristic methods should be applied.

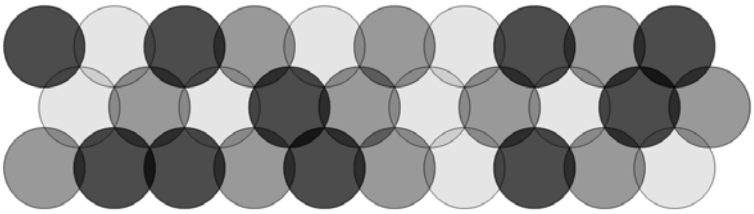
8. TECHNICAL ASPECTS AND PROBLEMS OF SHADING ARRAY BASED ON RANGE-2 CELLULAR AUTOMATON

Concept of this shading device is based on opto-mechanical system of square plates made of polarized glass. The coupled plates are transparent and become opaque when one of the them rotates by $\pi/2$ angle.

Such system requires local wiring only and every module is composed of five input cells connected to one output cell. Top row only is being directly manipulated, the rest of array changes by the means of local propagation within CA domain. Since range-2 CA gathers information from five upper neighbor cells, the wiring becomes fairly complex but fortunately the set of wires is exactly the same for each module, which makes the fabrication feasible.

9. CONCLUSIONS AND FUTURE WORK

- By implementation of Cellular Automata, it is possible to control the average opacity of a shading array and create very interesting patterns at the same time.
- Since "brute force" search methods of setting initial conditions fail at larger array sizes application of heuristic methods seems inevitable.
- Possible application of simple 2D CA. In case of 2C-2D-R1 (Two color, two-dimension, range-one) general CA at Moore neighborhood, the wiring becomes much simpler, ranging to the four very neighbor cells only. While Neumann neighborhood is more likely to create interesting patterns at slightly more complicated wiring (to eight very neighbors) it is still requires much simpler wiring than in the case of 1D-R2 CA.
- Possible application of totalistic CA. In such case, minimum number of states rises to 3, but from the elementary rules up, the number of rules for totalistic CA is significantly smaller than general rule of the same class and the manifested behavior is still very interesting.
- Implementation of hexagonal grid. A circular cell is placed between two glass panels. The mechanical parts would appear as an array of dots as shown below.



References

1. Theory of Self-Reproducing Automata. John von Neumann, (1966)
2. A New Kind of Science, Stephen Wolfram, 2002
3. http://mathworld.wolfram.com/CellularAutomaton.html