Author(s): Coates, Paul; Healy, N.; Lamb, C.; Voon, W.L.
Title: The use of Cellular Automata to explore bottom up architectonic rules
Year of publication: 1996
Citation: Coates, P. et al. (1996) 'The use of Cellular Automata to explore bottom up architectonic rules.' *Eurographics UK Chapter 14th Annual Conference*, 26-28 March 1996 London: Eurographics Association UK.
Proceedings ISBN: 0-952-1097-3-5

The use of Cellular Automata to explore bottom up architectonic rules

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This paper was presented at Eurographics UK Chapter 14th Annual Conference. held at Imperial College London UK

Abstract

This paper reports on recent experiments at UEL as part of the MSc:Architecture Computing & Design programme. Using a range of state change rules a series of processes have been explored that lead to transient ÒdesignsÓ whose global form is encoded in every cell of the development space. The application of CAs to Architectural Design offers a lower level of rule system acting on a more elemental deconstruction of architectural space than the topological methodology that many current spatial generators embrace.

Architecture, aesthetics and the utilitarian tradition

Since the end of the last century it has commonly been seen as decadent to simply ÔapplyÕ aesthetics to the structure of a building to make it beautiful (with the exception of the deliberately ironic, although irony itself would have been thought decadent by the stern moralists of the modern movement).

Architects such as Louis Sullivan, Mies Van der Rohe, Le Corbusier and so on used the example of engineering to help to explain the relationship between form and function. Based on the simplistic assumption that ÔengineersÕ do not design form, but that it emerges from the correct solution to mechanical realities (cf. the Eiffel tower, BrunelÕs bridges and the dom-ino concrete frame) the modern movement declared such objects as ÔpureÕ and ÔrightÕ. The functionalist tradition has suffered many blows in the last 50 years, partly because it was always an oversimplification, and partly because technology has now reached a point where the constraints of structure have almost vanished, with form becoming the precursor of function rather than itÕs determinant, ie. anything is possible (cf. Sydney Opera House)

The study of 3D CAs allows us to get back to a more rigorous analysis of the basic determinants of form, where the global form of an object not only should not but actually cannot be predetermined on an aesthetic whim. Thus with the CA we have an opportunity to experiment with the true determinants of form in a way that the pioneers of the modern movement would have relished - an aesthetic of pure function whose outcome is totally embedded in the function to be solved.

This paper describes a series of experiments carried out as part of the MSc programme , Computing & Design at the University of east London School of Architecture under the direction of Paul Coates. They were based on a 3D CA developed by MSc student Robert Thum, using Autolisp and Autocad , and subsequently elaborated by Chris Lamb, Niall Healy and Win Van Voon to explore different rule sets concerned with a range of morphological issues.

Developing the cellular automata within a CAD package such as Autocad (as opposed to building stand-alone software) has certain advantages, the main one being that the morphologies developed are accessible to further manipulation since they are held in the 3d database. In this paper we give an example of post-processing such data to form second order structures such as skins and warped surfaces, and generally the form can be viewed and rendered under a variety of mappings and transformations without extra effort. The eventual intention of the project is to develop a customisable CA engine with the ability to develop form under a wide range of state change rules within defined CAD environments, as a basis for a new kind of architectural modelling.

Introduction

This paper proposes a generative mechanism by which the genetic structure of any form can be accessed and manipulated to increase the possibility of an emergent architectural outcome. The basis of such a mechanism is information encoded in the form of state transitions between cells in a three dimensional lattice, an implementation of a three dimensional Cellular Automaton. The cells of the CA resemble those of a natural organism in two respects. Firstly, the behaviour and material form of the organism are controlled by instructions encoded identically in all cells in the developing organism. Secondly, the initial information or genetic structure, expressed in the CA as the combination of initial cell cofiguration and transition rules set, consists of a series of low level instructions controlling only local transitions between units, requiring a discrete generative mechanism to convert the one dimensional information to three dimensional form.

Current directions

Elements of current architectural theory and methodology that propose an alternative to established architectural methodologies, and in some instances adopt aspects of our new understanding of science, fall into three categories. Firstly methodologies that propose an alternative to the linearity and determinism of the traditional architectural design process and question the central control of the architect and hence the role of the architectural ego, secondly the proposal of a methodology based on the simulation of self - organising development and evolution of natural systems and thirdly, in certain cases overlapping with the two previous categories, are methodologies experimenting with emergent form in a virtual environment.

Kipnes (1992.) outlines current design methodologies that employ established architectural techniques, but propose fundamental revisions to the traditional design process. The established design process is one of a linear progression from source material to object and within which the architectural ego is central. Kipnis describes, the work two architects, Eisenman and Heyduk, and describes a re-emphasis to the traditional process by which the architectural ego is displaced or within which the use of specifically architectural source material is minimised.

The integration of techniques developed by the scientific community offer the possibility of a role for Genetic Algorithms within traditional design methodology as an optimisation technique for the the pragmatic elements of architecture, for example circulation. This is currently under assesment at Univesity College London, initiated by .Hillier & Penn as a joint programme between architectural practices and the University. Current work of Unit 11 at the Architectural Association, London (Frazer 95) is centered on the study of natural systems and development of self organising virtual systems employing the biological analogy of cellular growth in the context of a multistate Cellular Automata and genetic algorithm.

Clearly the work outlined above and in this paper is augmented by the work of the Artificial Life community which has experimented widely with both Cellular Automata and Genetic Algorithms. The substantial body of work based upon one and two dimensional CAs provide examples and applications for increasing the functionality of algorithms, for example, the extension of the radius of influence of the rule set relating to cells and the development of multistate three dimensional Cellular Automata described later. However a substantial ammount of research has been carried out on specifically three dimensional automata, and in several instances three dimensional networks have been applied to the simulation of natural systems. In respect of reseach into the behaviour of the system itself, of particular interest is the implementation of a three dimensional cellular automaton and continuing research and classification of forms and rules at the University of South Carolina, a develpoment of ConwayÕs two dimensional Game of Life. Additionally, Margolus and Tofoli have developed an hardware implimentation of a CA which, in its latest generation CAM Ð 8, contains a three dimensional universe. Using CAM Ð 8 the ATR Human Interface Processing Research Laboratories, Japan (Coveney & Highfield 95) are attempting to simulate the three dimensional network of the brain, in order to control an automaton. Further applications include the modelling of crystallisation, fluid motion and chemical reactions and are documented by Coveney and Highfield, 1995.

The experiments

The results presented below are viewed as forms of ALife, not as emulations or representations of life. The interest lies in their capacity to represent the complexity of architectural form by the implementation of an entirely new and in our view more appropriate methodology of parallel, non-linear information development. The genetic structure represents the method by which the cellular system can be manipulated. and consists of an initial three dimensional configuration of cells and a series of associated rule sets. Currently the user inputs a genetic structure directly, however our aim is to evolve genetic structures under competition in the environment. The CA can operate indipendently of the graphic system, but the behavioural information encoded in the state of each cell requires translation or interpretation to material form, the Series 3 experiments.. The distinction between the Series 1 and 3 experiments equates with LangtonÕs description of that the virtual and the material elements of an organism (Langton 88). The first series of experiments are concerned with the relationship between the genetic structure of the Cellular Automata and the resultant behaviour of the system, with the implementation of rules that exert pressure on the system towards an outcome appropriate to the specific virtual environment. The third series of experiments extract the information represented by the state and three dimensional location of the cells and translates the global state into a material expression. Access to the three dimensional database and solid modelling of AutoCad allows the behavioural information contained in the three dimensional array, visualised in the first series of experiments as cubes, to be translated into a variety of three dimensional material form, described in the Series 3 experiments

Experiments

Series 1

Section A

The first series of experiments were based upon research into the rules and finite forms of three dimensional Cellular Automata carried out at the University of South Carolina and published in Complex Systems (Bays 87,88)that concentrated on two elements of the system., Firstly the classification of rules according to the pattern of cellular growth and secondly the classification according to the behaviour of isolated or ÔfiniteÕ forms which are analoguous to the two dimensional oscillators, gliders and glider guns of the Game of Life. Complex Systems published the classifications and the discovery of new finite forms. The emergence of form is the result of totalistic or counting rules, expressed in a four figure notation. The first two figures of which represent the fate of on or live cells, the Ôsafe environment rangeÕ, the first representing the minimum number of neighbours for survival, the second the maximum. The third and fourth figures control behaviour of vacant cells, the third representing the minimum number of adjacent live cells for birth, the fourth the maximum. The cell at the Ôcentre of attentionÕ, refered to later, is the cell state to which the rule set refers.

States

State 0 is the empty cell
State 1 is the cell

Rules

- Centre of attention: occupied cell
- Rule number one specifies the minimum number of adjacent cells to remain in state 1
- Rule number two specifies the maximum number of adjacent cells above which a cells state becomes 0
- Centre of attention: empty cell
- Rule number three specifies the minimum number of adjacent cells required for birth
- Rule number four specifies the maximum number of adjacent cells required for birth

Initial experiments were simply the observation of growth from the combination of the published rules and initial three dimensional configuration, i.e. construction based upon previous experience, the most interesting aspect of which is the emergence of finite forms, which occur only when the initial configuration and specific rule set result in bounded or limited growth.

If one views all the possible forms resulting from all combinations of rule sets and initial configurations, the probability of the emergence of finite forms is extremely low. A method is required whereby one does not have to go back to the beginning when one already has an idea of a desired outcome. One possibility is construction based upon previous experiments, the other is an algorithm that increases the probability of a certain type of behaviour that is a prerequisite for, or increases the probability of, the emergence of the required behaviour. For example, the emergence of finite forms from optimised rules for bounded growth. Though written, experiments have yet to be performed to asses the validity of this approach. From these constructed observations the algorithm was extended to experiment with randomly generated rule sets and/or initial configurations, allowing the results of the implementation of different rules on identical initial patterns for example.

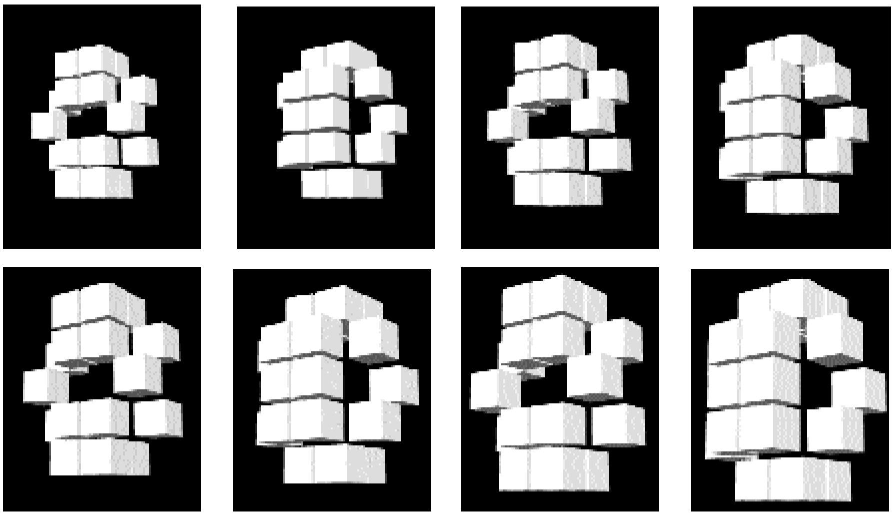


Figure 1: Eight iterations of the glider in the 5655 rule set

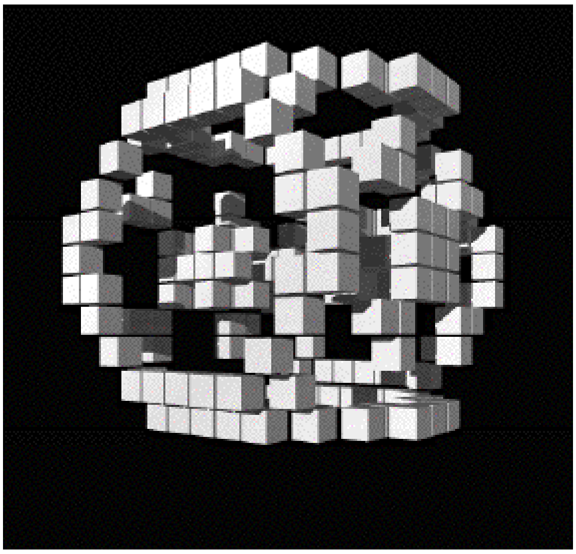
Using the analogy of the development of the genotype to phenotype in a specific environment from developmental biology, one can visualise a cell in the CA as a cell in a low level organism with an identical genetic code for the organism contained throughout the array. The environment of each cell is either the six or twenty-six identical cells in state 0 or 1.

The CA is analogous to a simple organism of one cell type in a environment comprised only of other identical cells. The experiments demonstrated the importance in the genetic structure of the intricate relationship between genetic structure and the emergence of finite forms, variation of the rules on identical configurations resulted in for example the difference between the constructed finite growth and oscillator of the 4555 rule and the unlimited growth of the 4544 rules. Interesting results were obtained by restricting any figure to less than 7 and greater than 2

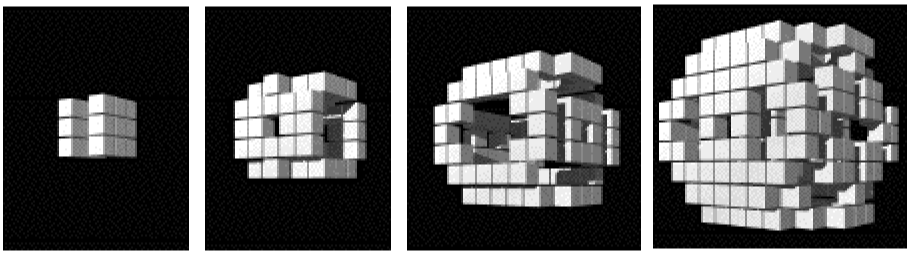
Rule 2424

Survival rules
Minimum survival number: 2
Maximum survival number: 4
Birth and death rules
Minimum birth number: 2
Maximum birth number: 4

The initial configuration of cells results in a global form in which discrete internal forms emerge within an envelope or skin.



Final iteration



Initial configuration Iteration 1 Iteration 2 Iteration 3

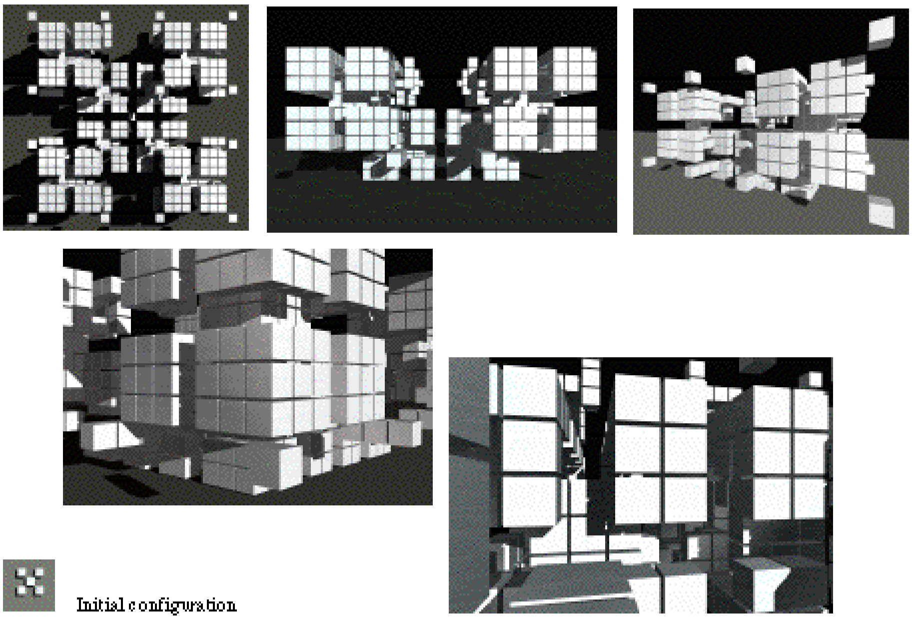
Figure 2: Iterations of rule 2424

Totalistic rules offer an opportunity to investigate the relationship between genetic structure and outcome, and demonstrate the generative possibilities of the parallel system, in which complexity emerges from simple rules. They simulate the complexity of life, but require expansion of genetic rules and a more complex environment to more accuratly represent the complexity of the architectural process and resultant form.

Section B

To develop the proposal for the parallel development of information, held in the genetic structure and contained in cellular units and to more accurately represent architectural development, the rules for growth were extended to include not only the number of cells required for birth/death and survival but also the spatial locations of the adjacent cells. The growth rules firstly defined the spatial location of cells that were to be taken into account in the calculation of a state transition of a cell, the Ôvoting rulesÕ and secondly defined the birth/death and survival rules in the familiar four figure syntax, the Ôcounting rulesÕ. .It is possible to specify a neighbourhood that is a sample of the Von Neumann or Moore neighbourhoods and therefore constrain development in any direction. A more subtle method is to specify the number of cells in any plane adjacent to the cell at the centre of attention. Based upon the experiments in section A, it became possible to identify initial configurations and rules that predicated a certain outcome. The most architectural results were those that resulted in a definite series of discrete sub- forms throughout the array within an envelope.

In this example, the influential cells are the 8 cells on the same layer as the cell at the centre of attention, the 9 cells in the layer below the cell and the 1 cell directly above the cell. From this sample, the counting rules are 2524.



Initial configuration

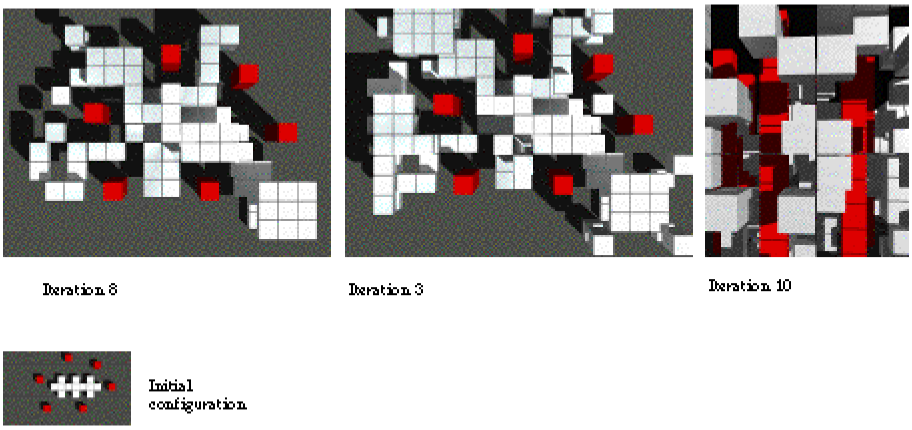
Figure 3: Rule 2524 with voting rules at tenth iteration.

Section C

The complexity of architectural form requires numerous distinct component forms acting cooperatively within the global form. To represent the complexity of the relationships between various information structures and to develop this information in parallel, the numbers of states of the CA were increased. Additionally, based upon the experiments above, the instructions are expressed as not only counting but also voting rules. The rules define the behaviour of the cell in relation to the specific state of adjacent cells, to increase the complexity of the environment, informed by the viewpoint embodied in KellyÕs (Kelly 1994) quote that Ò... the way to get lifelike behaviour is not to try to make a really complex creature, but to make a rich environment for a simple creature.Ó This represents the modelling of the process of ÒnegotiationÓ between a cell or organism in its respective environment.

Cells transitions from state 0 to state 1 are controlled by counting and voting rules, and growth is prevented in the 8 cells adjacent to a cell in state 2. The syntax of the birth rule is to firstly define the influential cells and express the rules as; Ôif the number of cells in state 1 is between x and y (birth rule) and any cell adjacent to the cell is not a cell in state 2, then state changes to state 1Õ. Specifically in this example, the influential cells are the 8 and 9 cells adjacent to and above the cell at the centre of attention and the one cell immediately below the cell.

Cell transitions from state 0 to state 2 are controlled by a voting rule that states that if a cell is in state 2 adjacent and below a cell in state 0, the state of the cell will become 2 in the next iteration, i.e. state 2 cell growth is constrained vertically. These rules provide for the equivalent of obstacle avoidance.



Iteration 8

Iteration 3

Iteration 10

Initial configuration

Figure 4: Cellular development obstacle avoidance

In the following examples, where development is more complex the zone of avoidance is three dimensional. The experiments fall into the following categories defined with respect to genetic structure:

- Identical initial configurations and various totalistic and voting development
- rules i.e. growth is constrained by restrictions on rate and
- direction of growth.
- Different initial configurations and identical totalisticand voting development rules Different initial configurations and totalistic and voting development rules i.e. a number of different genetic structures within the same three dimensional array.

In the calculation of the state transition from 0 to a particular state, each state transition is locally controlled by three types of rule:

- Rule type one specifies the spatial position of cells that are to be considered in the
- calculation of the new state
- Rule type two specifies the birth rules for the particular state by stating the
- minimum number of similar cells and the maximum number of particular cells for a
- state transition
- Rule type three specifies the zone within which a state transition cannot takeplace.

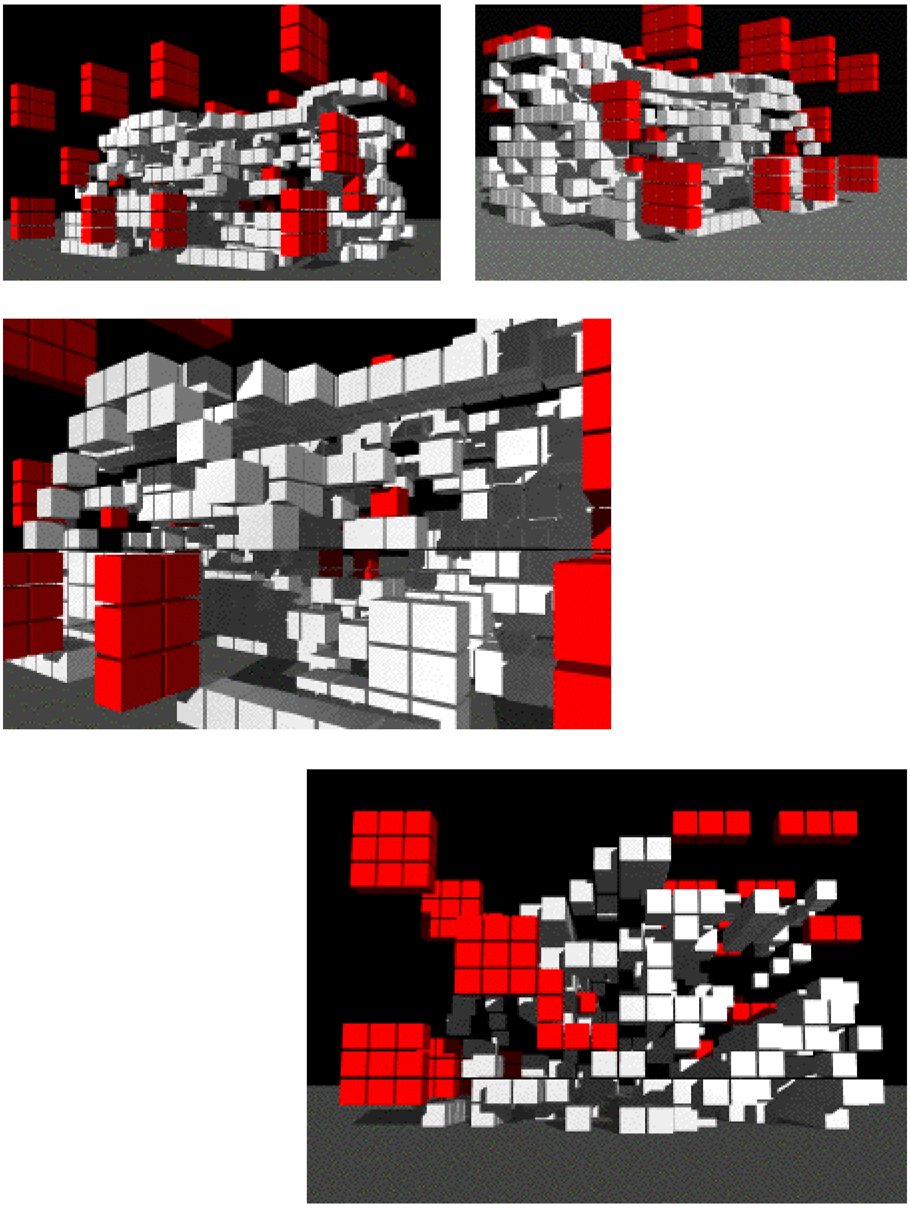
In the calculation of the state transition from a particular state to 0 and no transition states, each state transition is locally controlled by counting rules only which refer only to the number of identical cell states in the defined neighbourhood.

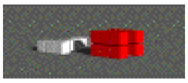
With reference to figure 5: State 0 is the empty cell with transition rules coding for one of the following states

- State 1 with counting rules
- State 2 withcounting rules

The resultant forms, with contrasting genetic structures, and discrete developmental programmes, compete in the environment for development opportunity. The rules also permit no growth in the three dimensional zone of 26 cells adjacent to cells in a different state.

The genetic structure of the form comprised of state 1 cells has permitted more prolific growth, resulting in a coherent form and distorting the spatial pattern of state 2 cells, resulting in a series of oscillators, in this case three dimensional blinkers. The counting rules are 2525 and 1325 for the two states.





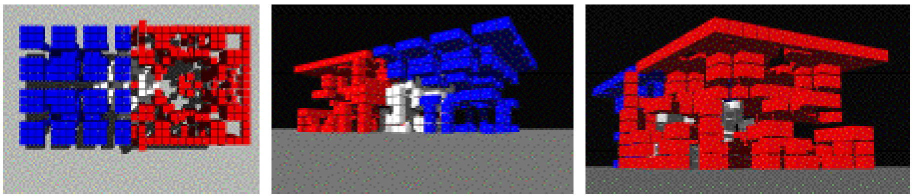
Initial configuration

Figure 5: Multistate automata after ten iterations with counting and voting rules

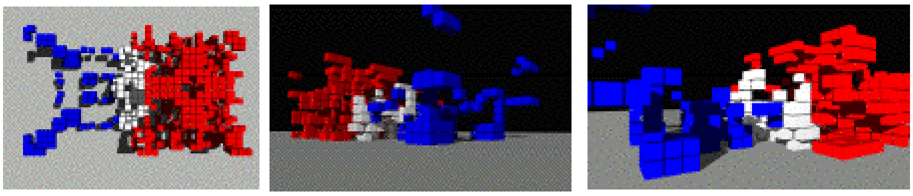
In the following example the genetic structure of the three resultant forms is different. Refer to figure 6.. The structure of the state 2 and 3 cells are relatively similar, the structure of the state 1 form is entirely different.

Each state is influenced by an identical spatial array of similar cells. Development is not permitted in the three dimensional zone of the 26 cells surrounding a cell of a different state.

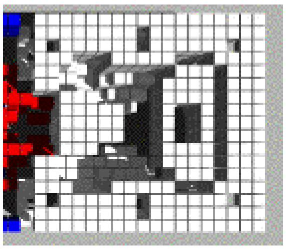
Specifically the voting rules are identical to the previous example and the counting rules are, for each of the three states; 3525, 2525 and 1515.



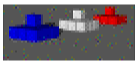
Plan after 6 iterations



Plan after 8 iterations



Plan after 7 iterations



Initial configuration

Figure 6: Multistate automata after various iterations

Section D

The final series of studies are directed at developing a realistic architectural response within a relatively complex environment. Based upon the multi state experiments of Section C, a refinement to the programme was introduced which extended the zone in which cellular growth of cells of state x is not permitted adjacent to cells of state y or z and vice versa. The zone can be extended to any distance and can relate to the relationship between any specified states. The concept is more commonly found in one dimensional CAs, and is referred to as the radius of influence.

The rule types and specific rules are as follows

State 0 to state 1

Voting rules, the influential cells are the 8 cells on the same layer as the cell at the centre of attention, the 9 cells in the layer below the cell and the 1 cell directly above the cell.

Counting rules, Avoidance rules, reaction to state 3 cells:

cell transition to state 1 is not permitted if a cell of state 3 is within a radius of 5 cells in the cell locations east, west, south and north of the cell at the centre of attention, reaction to state 2 cells, cell transition not permitted in a zone immediately adjacent to a cell in state 2.

State 0 to state 2 and 3

Voting and counting rules, transition to state 2 if a cell immediately below the cell at the centre of attention is in state 2

State 1 to state 0 or 1, counting rules only, as above. State 2 to state 2 and 3to 3, no death rules.

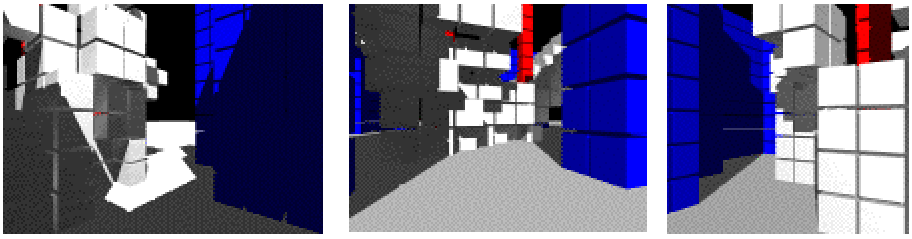


Figure 7: Views after ten iterations

In the previous experiment, the cell at the centre of attention has the ability to respond to environmental influences that may be at an infinite radius, yet the response remains local in terms of the global pattern. This element of the routine was again modified to apply pressure for a specifically architectural response, that of the emergent forms response to overshadow from adjacent static of emergent forms. In addition to all other rules, the cell at the centre of attention has the ability to sense overshadow and therefore remain in state 0.

Series 2

In an experiment with multi state CAs, Voon initially experimented with abstract systems based on a development of the growing and obstructing cell scenario just described in this paper. One development that proved fruitful was the development of special state change rules that depended for their effect not only on the number of cells in a region (as in the life game) but also on their relative positions. Also, the system was changed from the standard life game scenario of birth and death rules to one of just birth rules, a development of the classic Ulam automata originally described in Burks Ed. (1970)

The *sunshade* CA is a three state cellular automaton with rules based on both counting and direction, so that the influence of environmental considerations can be explored. In this system the environmental influence is assumed to be that of orientation, with the aim of generating sheltered open spaces with one particular orientation, a kind of ÔbalconyÕ idea. The neighbourhood is a 6 cube region of the face joining cells to a cube. The south direction is assumed to be the sunny side, and southern cells are treated differently to other directions. There are no rules for death, once a cell has been set, it remains set.

The states are:

- State 0 is the empty cell
- State 1 is the cube cell - assumed to constitute a built accommodation unit
- State 2 is the plate cell - assumed to be a balcony or other outside space

with the following rules:

Rule 1)(0>1)

An empty cell can turn into a solid cell (ÔroomÕ) if it has a solid room cell either east west above below or south of it.

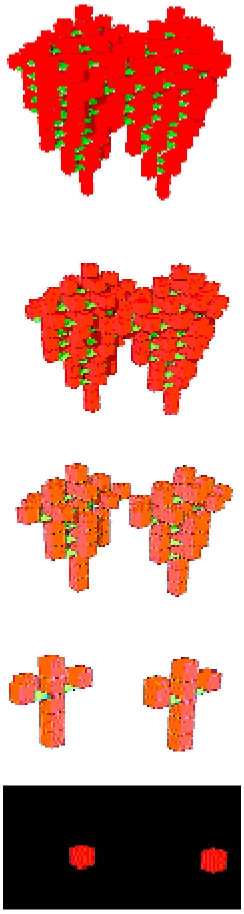


Figure 8 : The sunshade CA version one

Rule 2)(0>2)

An empty cell will turn into a flat ("balcony") cell if there are three room neighbours in the east west and north positions. The result is a series of recesses on the south side and terracing effects towards north, north-east and north-west. While this was partly effective, the rules did not preclude embedded balconies whose aspect was blocked by further growth. The limited scope of the neighbourhood rule meant that some green cells were behind red cells.

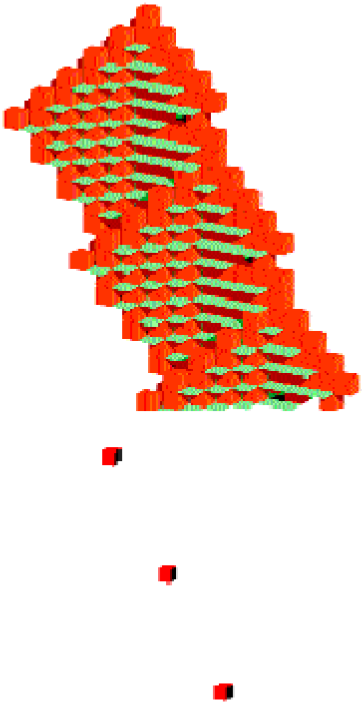
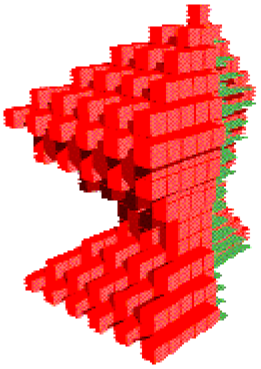


Figure 9: Three seed sunshade CA, second version

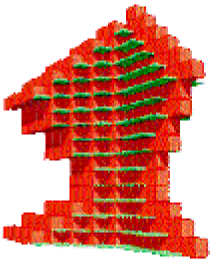
In an attempt to counter this blocking effect, the cell neighbourhood was increased to a twenty-six cube region surrounding the relevant point.

- Rule 1) An empty cell will turn into built form if it has one neighbour in the
- west, east, southwest, southeast, above or below position.
- Rule 2) An empty cell will turn into a balcony if there are built cells present
- on east & north and west & north (ie 4 altogether).

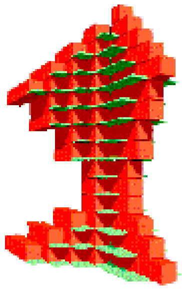
This produced a symmetrical growth pattern with a much more controlled development of balconies. The illustrations here show views on both sides of an automaton developing from two 3 seed cells



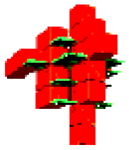
Series 3



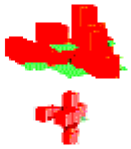
The final set of experiments address the question of firstly how cells self-organise and secondly how they develop into specific tissue types, ie. the forces which determine the architecture of the organism. Each cell contains a copy of all the developmental instructions and each cell has the potential to become any tissue type therefore there must be some organising principle at work Wolpert (Wolpert 91) has developed the theory of Òpositional informationÓ which addresses this question.



Wolpert suggests that in a developing organism, Ò ....by reading the concentration of morphogen,. cells would know their position.. . more generally, if cells have their positions specified and have the genetic instructions as to what to do at each position , a wide variety of patterns could be generated.Ó



This theory is challenged by Reproductive Biologist Jack Cohen and Professor of Mathematics Ian Stewart in their book the Collapse of Chaos (Stewart & Cohen 1994). Although they recognise that Ò...this a very flexible system.Ó they also feel Ò ...that the main problem with Wolperts theory is that in some respects it is too flexible; it allows for more variation than actually occurs.Ó



However, Positional Information theory provides a useful analogy which can be applied to a method of visualising the organisational architecture of the CA. The following describes an experiment which uses an information/data filter to identify a position/condition of a cell within the CA environment.

The Information/Data Filter

To develop the data filter it was necessary to design its operation around the structure of AutoLISP and the drawing functions available in the AutoCAD 3d database. The following explanation of the operation of the filter describes how all the live/on cells which exist on the perimeter are isolated and visualised as a skin which encloses the mass of live cells.

As already mentioned, the CA is an organisation of information. In AutoCad this information is organised into a list of numbers, the numbers relating to the state of the cells and their position within the list which relates to the location of cell within the CA environment.

The point at which the data filter engages with the operation of the CA is the moment that the programme establishes if a cell is alive/on or dead/off. If the cell is alive/on then instead of inserting a cube to identify the state of the cell, the co-ordinate information (it's position in 3d space) is recorded. This information is added to a separate list in the data base.

The Operation of the Filter & Visualisation Routine.

When this list has been constructed after each iteration, it is passed to the filter & visualisation function. The filter function then begins the process of identifying the cells that exist on the perimeter condition.

Firstly, it sorts the list into sub-lists with the same Z co-ordinate . This isolates the live cells co-ordinate on each consecutive layer through the CA environment.

Secondly, it sorts out the sub-lists into sub-lists with the same Y co-ordinate . This isolates every Y axis throughout the CA environment that contains live cells co-ordinates.

Finally, the first and last co-ordinates on each y axis containing live cells are selected and organised in a list that is passed to the visualisation part of the programme. This list therefore contains the co-ordinates of all the live cells that exist on the perimeter of the mass of live cells.

Within the AutoCad 3dimensional modelling environment the drawing function Edgesurf creates a 3d surface between 4 connecting polylines (Pline). Having isolated all the perimeter cells on each layer of the CA the co-ordinates are passed through the drawing function Polyline to create the contours of the external surface. The first and last points on each of these contours are then connected vertically with a further 2 lines. This operation is carried out sequentially for each pair of consecutive contours. As each set of 4 polylines are created they are passed to the Edgesurf function to create the skin enclosing the mass of live cells which in the CA environment. The following images (Figure 11) illustrate 2 experiments with the data and visualisation filter, using the CA with counting rules described earlier in this paper. In these experiments the initial seed pattern remains the same for each rule set. Adjacent to the data and visualisation filter output is the cube insertion method of visualisation, this illustrates the quantity of cells that exist within the skin that encloses the mass of live cells.

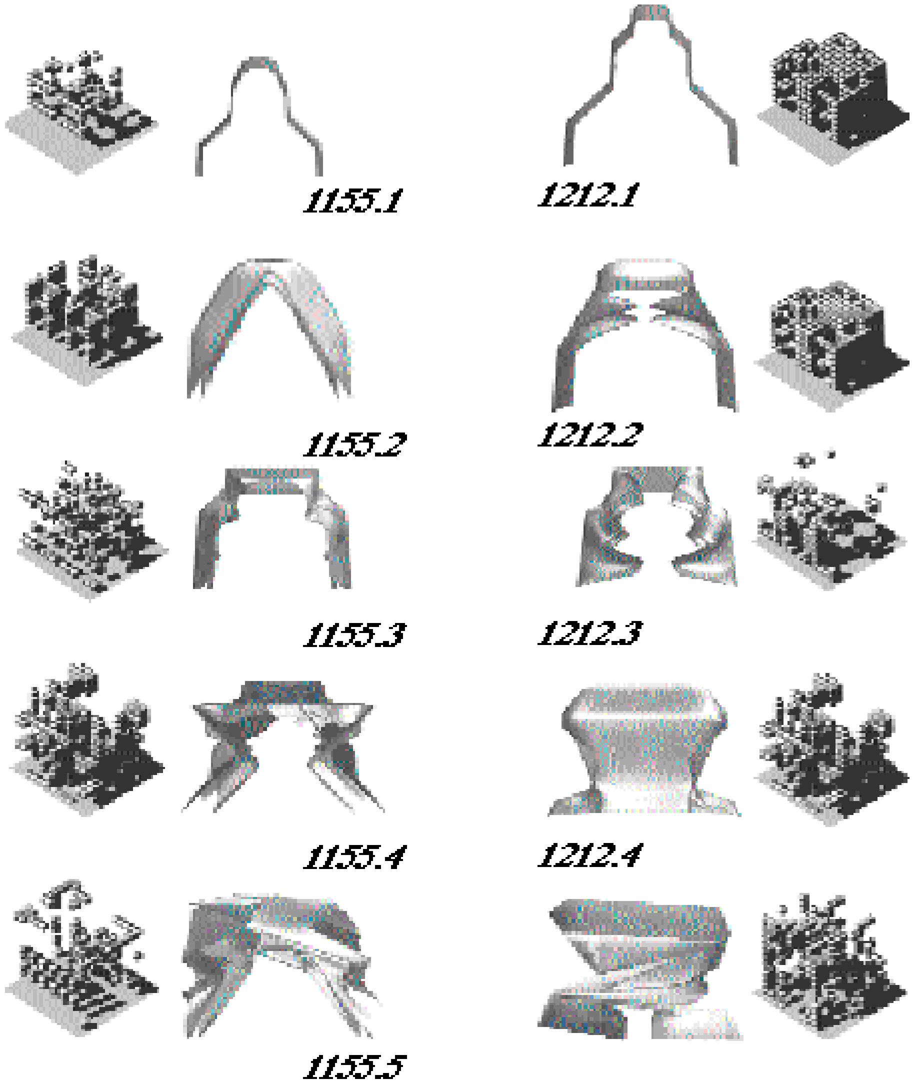


Figure 11: The two visaulisaition methods, external skins and theit associated mass of cells

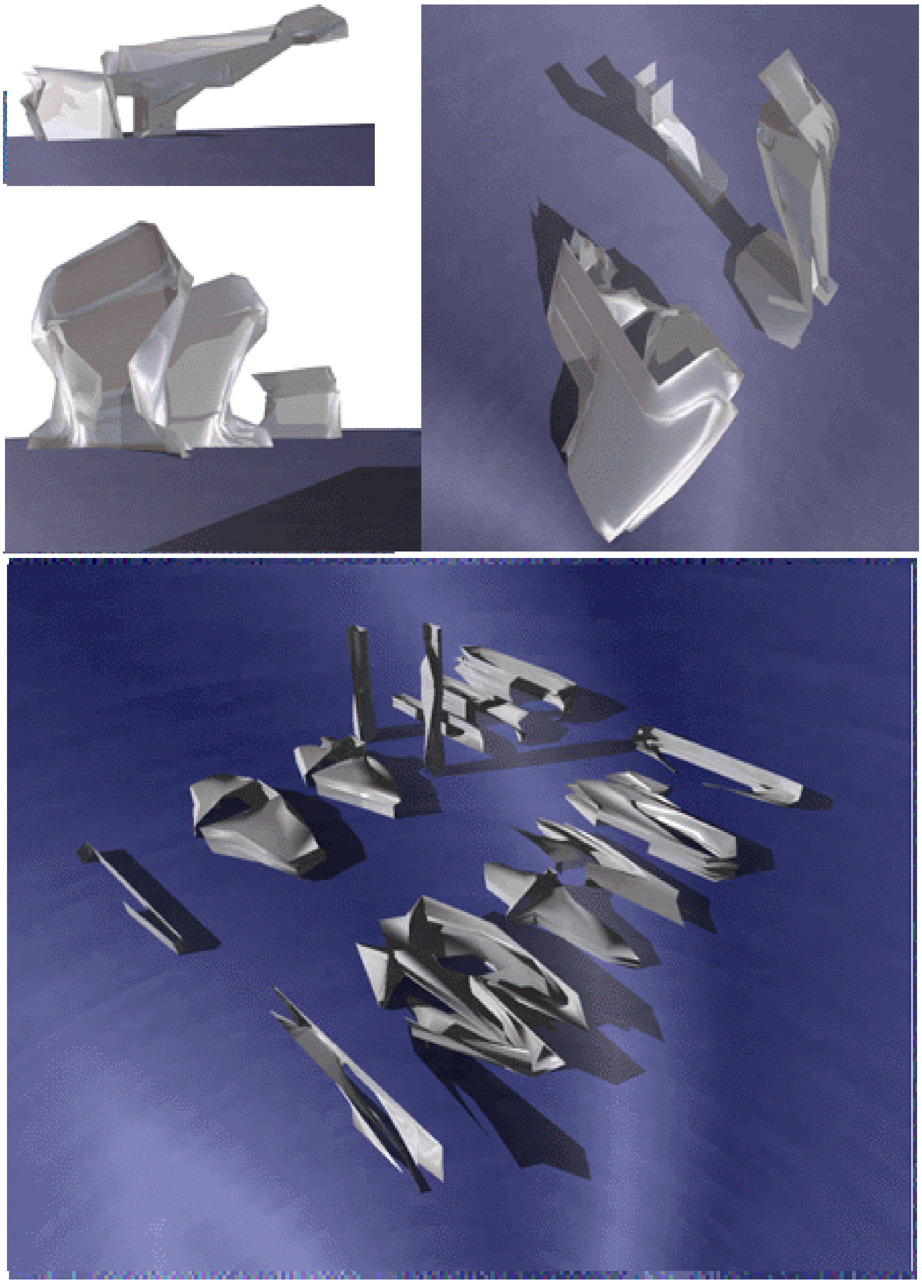


Figure 12: These images are the result of random investigations into the CA's ability to create form from rule sets and visualisation techniques discussed in this paper

The function of the filter is to identify and isolate the location of a specific condition that exists within the CA environment. This information then uses the 3d modelling ability of AutoCAD to map the form of this condition. However the information isolated by the filter is only used by the post processing visualisation function.

Further development of this programme will be to incorporate a feedback loop whereby the information isolated by the filter in previous iterations will influence the organisation of the CA in future iterations.

One possibility for development is to run lists which contains information on previous conditions in parallel to the alive/on state list in the database. This "memory " of previous states may then be incorporated into the transition rules, referred to earlier in the paper. This would allow the "memory " to influence directly the state transition of each cell which inevitably effects the global organisation and forms.

As referred to in the introduction of this paper, the development of the CA within a CAD package such as AutoCAD is essential if a variety of methods for visualisation are to be developed. The pallete of modelling and drawing functions within AutoCAD will allow a variety of visualisation methods which may to be applied to filters that isolate the range of conditions and states that exist within the organisation of the CA.

However, the experiment and proposal elaborated on so far do not address the issue of the selection of form. To develop the CA as a useful architectural modelling tool it will be necessary to assess what the architects of the modern movement would describe as the forms fitness for purpose . Creating the algorithms which can describe purpose and assess fitness will be the subject for further development of the Cellular Automata in the field of architecture.

"I have called this principle by which each slight variation , if useful is, preserved by the term Natural Selection." C. Darwin1859

Conclusion

Cellular development

This paper represents work on the behaviour of the automaton visualised as an array of cubes representing the various states, and the alternative formal and material visualisation of this information has progressed discretely. Our intention is to develop the algorithm to allow the visualisation of the information in both forms, and to allow interaction based on the visualisation of both behaviour and form. As a development to the Series 3 experiments, the extended radius routine could be used following to assist in spatial organisation and pattern formation within the emergent form. A certain positional identity could be linked to a specific set of genetic instructions encoding the different components of the emergent form.

The work described in this paper was undertaken using AutoCad v12 and Autolisp, and was rendered using StrataVision 3D. We plan to develop this work using the Reflex 3D modelling environment running on Silicon Graphics Hardware, with scripts written in VEL (a C like scripting language). References:

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