Cellular Automata, Memory and Intelligence

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Abstract. Understanding memory as the faculty by which a system stores and remembers information from the past to a new purpose with shapes that are emerging as "collective designs"(a repository of built information), this research works with the demonstration in how CA can generate a trace of its existence as memory based on the activation and deactivation of the discrete system in which grows, like a footprint in the affected area of intervention, improving a "stigmergic operation" in the field, conditioning the following steps in the collaborative growing of this basal structure. Based on sets of digital experiments, a set of CA using Langton Ants generates different solutions based on the activation and deactivation of rules according to information coming from patterns, creating spatial solutions that deal with built memory three-dimensional emergent structures.

Keywords: Cellular automata · Memory · Intelligence · Digital design · Generative design · Digital theory

1 Introduction

In nature, we can find some examples of bottom-up design application in contrast to a top bottom classic design approach, creating shapes that are complex but efficient at the same time, dealing with problems collaboratively with optimal use of available resources and a maximum performance related with shapes that are emerging as "collective designs" being the fruit of this collective interaction (Fig. 1). Examples of this design way from nature are, for instance, social insects like Ants that are building intricate underground structures that are built by generations of coordinated builders through the whole structure, which acts as collective memory (as a catalyst of development, brings the opportunity to any system natural or artificial to retain information from past events to possible new steps). This structure (as a repository of built information) continuously optimizes resources by the feedback action from the memory storage to a new action or movement, working as a predictive manual of probabilities instead of a rigid process of rules (deterministic).

This process is the first step through which any organism can learn, as a set of continuous improvements over existing reality. The previous aspect (as a predictive model) can develop a growth strategy as a target to follow from the starting point or state 0. The learning process can never end if the environment is dynamic and in constant change,

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generating a continuous review in the whole generative process. If the environment does not have changes due to external or internal actions (by the action of exogenic elements like whether or endogenic like our system immerse in this context), the system can not evolve, going into a dead state due to lack of stimulus, entering in a close loop (repeating the previous step deleting the last one).

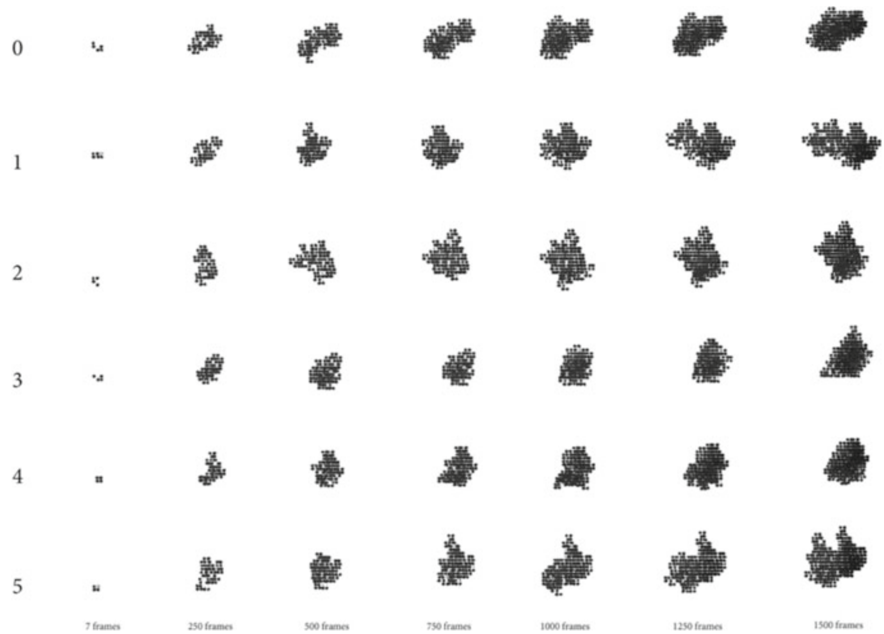

Fig. 1. 3D movements and five 4D generative variations using 6 directions (x, y, z, −x, −y, −z) based on a time line, recording the previous steps as visible generative memory. A discrete set of 3D rules working in a 3D space can build a 4D movement map. Image from the author

2 Memory and CA

Understanding memory [1] as the faculty by which a system stores and remembers information from the past to a new purpose 1. In the architecture field, this concept can be translated as a design that can store information and process it, with the possibility to evolve from an initial state 0 to a new stage: reading, learning and applying from its context of development. In that sense, memory can be used as a design tool, learning how to create a specific scenario of evolution compatible with the project nature. In this context, it is necessary to store the information of each evolutionary step for newer generations of growing and, following this methodology; architecture can iteratively evolve into a complex system being itself its own memory.

In that context, we can find cellular automata as one of the complex systems that can create shapes from 1D, 2D and 3D by the application of these bottom-up design principles, in where at the end, our role as designers is out of the final object, instead of that we can design the small relationships between every element of the system, discovering our final results as part of a try and error debugging process of our designs.

CA as a generative physical simulation system works with time, in which past, present and future are agents of redesign, working in the simulated nature as associates, where the feedback becomes from the future to the present as information processed, developing structures and patterns over and over again as a no-end cycle of design, being at the end, the synthesis of memory in the system. Each layer of information (from the base to the top) need to be recognized easier by the new generations in the system; as it is easy to recognize layers of growing in a tree, slicing its trunk, reading each step of development from the begging to the end, as well as in other example, crystals can create amazingly complex and intricate forms, which a clear starting point and a clear end, when the system can not grow more due to the lack of conditions to develop more steps, following the original expansion rules.

CA works like an enormous computing architecture [2] that can scale to high-resolution patterns, based on finite-state machines (also named finite-state automaton, it is a computation model that simulates a sequential logic), arranged in a discrete network, allowing local interactions with its neighbors [3]. These geometric orders (coming from crystal growing simulations) are the base in which the atoms are arranged in nano-metric scale by bounding phenomena (atomic stickiness), from pure orders in which the inner lattice between atoms is perfect (crystalline) to small crystals arranged in different directions (polycrystalline) to solids without arrangement (amorphous). Any of these kinds can coexist, building intricate shapes, increasing resistance to stress if more complex is the alignment between atoms. Understanding the previous examples, it is possible to design new rules, creating patterns into specialized data fields, using criteria of morphology, physiology, anatomy, behavior, origin, and distribution as integrated rules in the design and its relations with contextual changes.

The lattice and array rules can simulate these complex and hi-resolution geometries, extrapolated from this natural world to the design approach, understanding similarities in the representation language (graphic code) with other rules from the complex world of Escher [4] and the geometrical theories of William Huff [5]. In both references, the authors read the complexity as a set of rules, retaining the initial form information, from simple to high-density patterns to where any shape can go.

The first set of rules from these geometrical transitions are one of the initial keys in the growth as an evolutive design from an existent geometry (in this case, an origin A) to a possible destiny (the evolution to a B shape). According to Hofstadter [6], the transformation rules in a 2D deformation device are: *lengthening or shortening a line; rotating a line; introducing a "hinge" somewhere inside a line segment so that it can "flex"; introducing a "bump" or "pimple" or "tooth" (a small intrusion or extrusion having a simple shape) in the middle of a line or at a vertex; shifting, rotating, expanding, or contracting a group of lines that form a natural subunit; and variation of these themes… "a line" or "a vertex" is actually a reference to a line or vertex inside a unit cell, and therefore, when one such line or vertex is altered, all the corresponding lines or vertices that play the same role in the copies of that cell undergo the same change.*

We need to understand that points, lines, and containers (a unit cell as original) are the minimal geometrical units for a transformation in the parquet systems rules. The original shape is the masterpiece in all the evolutive logic because it contains the starting set of movement. It is possible to go from one origin to a different destination or vice versa. Using this method, it is feasible to achieve a high level of intricacy in the geometrical progression, understanding the possible movements (rotations and translations), as generative rules with a certain number of variations and steps of evolution, as an incremental factor of complexity (Fig. 2).

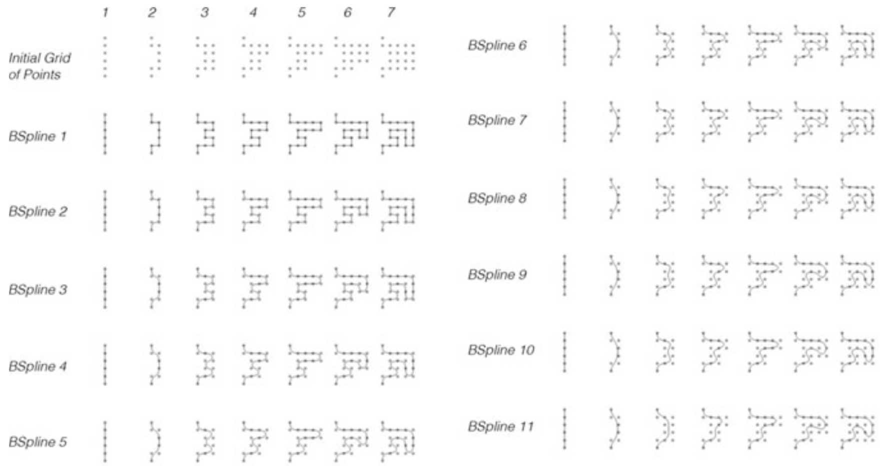

Fig. 2. Discrete evolutive rules in a 2D grid applied to a parquet system using a set of 7 evolutions and 11 BSpline types, Based on Kraig S. Kaplan works. Image from the author

Based on the previous concept, it is possible to understand how powerful this tool is to achieve memory capacity in architecture, using the topological approach as the container of pre-existent shapes, colors and textures, being feasible to adapt these geometries to a new evolutive scenario. Following these logics, any pre-existent shape can be used as initial material (such as an in-material building block) only if the next steps in the evolutive result are coherent with the first topological container, generating a dynamic structural progression as the prime structure for the whole system.

Nature always tries to find the most efficient shape available for each specific problem; in this case, shapes, as a result of memory accumulated in the system, are answer redefined in each moment, being perfected over time. Each growing pattern identified from the natural kingdom has a strong relationship with the geometrical world, matching many times with formulas that explain the procedure which made possible the existence of this shape in the natural world: “How these natural patterns are constructed may tell us something about how the far more complicated forms of animals and plants are created by a progressive division and subdivision of space, orchestrated by nothing more than simple physical forces”.

Linking this geometrical approach with the natural abstraction of minerals (one of the original ideas from John Von Neumann), it's possible to cross these two "different universes" in the same proposal. As the first point, we need to understand each tessellated geometry from the mineral arrays as a tridimensional "topological container" which is designing the initial set of rules of the artificial growth in the project. Secondly, from the site, each container can reload specific information to be evolved inside the growing, as a memory heritage for the following steps in the system. Points and lines are unable to store information without coordinated work as growing sequences. With this collective skill, they can reach the ability to store memory as a graphical map with clear coordinates, a first step to translate these generative shapes to a real project.

These shapes are linked with a specific function in the environment, evolving from circles and spheres (as the most efficient form) to triangles, squares, hexagons and many others by necessity, only looking at structural competence according to specific problems (like a honeycomb based on hexagonal patterns). For the previous reason, it is possible to argue that, from the same shape, it is feasible to obtain different results changing only a few factors, in many cases linked with probabilities and combinatory.

3 Self-intelligence

CA is linked with [7] artificial intelligence (AI), in particular with the simulation origins of artificial life, is one of the most representatives self-organizing artificial systems, together with neural networks and genetic algorithms, working as a structural analogy of intelligence, coming from large systems developed with simple elements having only local interactions, (a seed interacts with its own neighbors, which are usually just the cells closer to the seed as an activator), like crystal growing elements from a saturated media, working as a self-organized system [8], highly coherent in the whole generative structure, showing patterns and behaviors in a decentralized non-controlled system (Fig. 3).

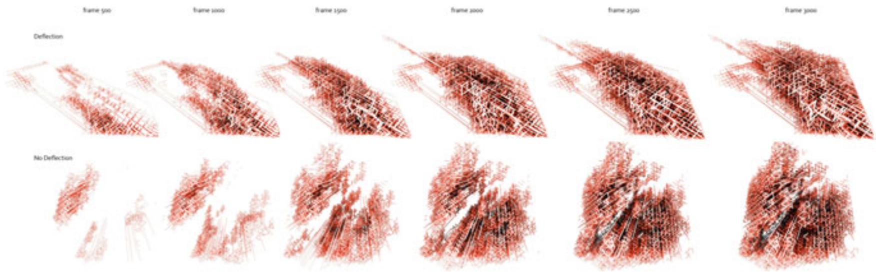

Fig. 3. Discrete CA rules in a 3D grid applied to a Basic Langton's Ant, A seed as constant activator between 0 and 1 and from 1 to 0 as Asynchronous CA (where only one cell is active at each time step, and the transition rule specifies the fate of the activation) Image from the author

The architectural body has changed from a static matter to a dynamic element, being possible to imagine a system that can learn and read complexity from the 4D space in which they are "growing", assuming movement and evolution as inherent parts in the design project. This concept of "live organism" has been defined as "hyper-body" [9], in which the building is a live system with capabilities of evolution, change, adaptation and interaction in where any form must have a certain degree of memory retention, recognizing its origin and proposing new spaces based on this concept of dynamic space deformation that can be understood as contextual project adaptation.

By convention, self-intelligence [10] is the ability to acquire and apply knowledge and skills by itself, belonging to this the artificial intelligence meaning, in where is possible to identify two different kinds: the vertical intelligence (from the top to the bottom of the system) and the collective intelligence (well known as bottom-up). The first one is highly structured and hierarchical by concept, which means that some control systems can take decisions over the whole components, affecting the total performance in a non-democratic action (as a god finger controlling everything) or a panoptic system all at the same time). On the other hand, the collective intelligence works as a self-generated organization, composite by agents as minimum organizational structure, by which the information shared between each member as local or collective trace can produce a highly diverse and complex result, only using simple rules shared with one or more system members. In this second system, the result could be read as a graphic or constructed historical registry of events, which at the end is the collective memory, built layer by layer in the life sequence. The sequence can be read by old or new agents, being reloaded for the following growing generations. The adaptability mechanism is founded in the system flexibility (collective intelligence) instead of the rigid organizational structures (vertical organization rules). In the end, adaptability is the catalyst of evolution for live organisms, from a 0 state to the next step in a generative way over the evolution of all its components which are interaction by simple local relationships, emerging at the end complexity behaviorally and spatially.

In that sense, this research works with the demonstration in how CA can generate a trace of its existence as memory [11] based on the activation and deactivation of the discrete system [12] in which grows, like a footprint in the affected area of intervention, improving a "stigmergic operation" [13, 14] in the field, conditioning the following steps in the collaborative growing of this basal structure (Fig. 4).

In synthetic systems (non-natural), memory has been related to how artificial structures are connecting current and new behaviors with old experiences, dividing the memory into two main groups: Short Term STM (containing the working memory) and Long Term LTM (collecting declarative and procedural memories). These memories are implicit or explicit, such as Ants, Bees, Termites, in which many times the STM records in the LTM during the time. Understanding that the working memory has an individual effect in each subject belonging to a colony, the constant repetition of behaviors can record a collective LTM, generating a spontaneous Procedural Memory, which is, by definition: non-conscious accessible memories like habits behaviors and stimulus–response conditioning. This kind of memory has a wide application in computer-simulated systems, firstly like Ruled-based systems, where explicit computational constructs encode a process, operation, or temporal experience. Secondly, the online learning of artificial neural networks is based on experience in neuroscience-inspired architectures. Thirdly,

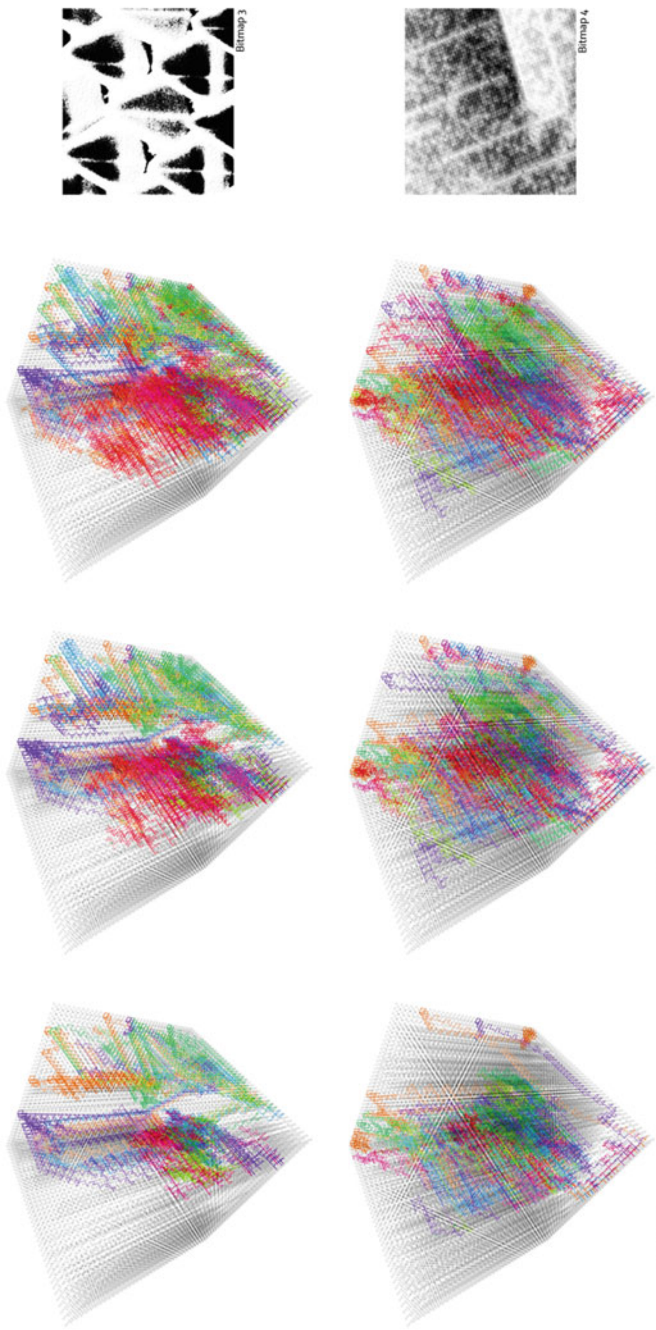

Fig. 4. Discrete CA rules in a 3D grid as a stigmergic operation working on an environment created by grayscale images. The red structures follow the structures from the different previous generations as “memory”, optimizing the steps from the bottom-up growing direction. Image from the author

developmental robotics models, particularly systems for acquiring sensorimotor coordination, are relevant given the explicit necessity of experience. In the case of these experiments, the generated structure works as an LTM for each Asynchronous CA seed, reading the previous steps as "paths" to follow. The CA seed is programmed as a "map reader", expanding the traditional range of neighborhood interaction; usually, one additional cell surrounds each seed according to Von Neumann and Moore models (Fig. 5).

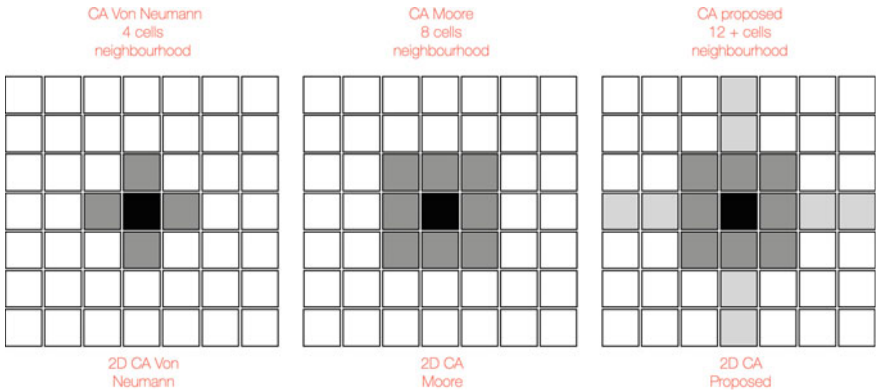

Fig. 5. Von Neumann, Moore and Proposed CA neighborhood interaction model from a CA seed

Based on sets of digital experiments, a set of CA based on Langton Ants [15] as an asynchronous model, together with the expanded neighborhood criteria, the CA system can create a final approach in which the activation and deactivation of rules according to information coming from patterns, can effectively build spatial solutions that deal with built memory three-dimensional emergent structures (Fig. 6) as a coordinate system in which is possible to create certain levels of interaction between "seeds", adding to the system some conditions of Separation, Alignment and Cohesion in a primitive way [16]. In this sense, the assignation of intelligence is quite near to the system capacity to apply the knowledge based on previous experiences in ongoing or further scenarios, no matter if the structure has a large number of different experiences accumulated along with a range of time, the important are principles running and how they are threading relations between two or more agents in the whole organization, as the rules working in a swarm: move in the same direction as your neighbors, remain close to your neighbors, avoid collisions with your neighbors.

On these experiments (as artifice life digital simulations), memory and self-intelligence can be appreciated in similar ways as in the termite mound plaster negatives of Dr. Turner [17] as a highly complex structure, generated by the action of termites (as collective intelligence) working with a simple implicit set of rules linked with specific features of their environment. Stigmergy is the indirect communication taking place among individuals in social insect societies [18], has the labor of the main generator of collective intelligence, as a repetitive work along centuries, generating pheromone traces, which allows the communication by trace, producing specificity in the colony group members, and building the history layer by layer, generation by generation. In

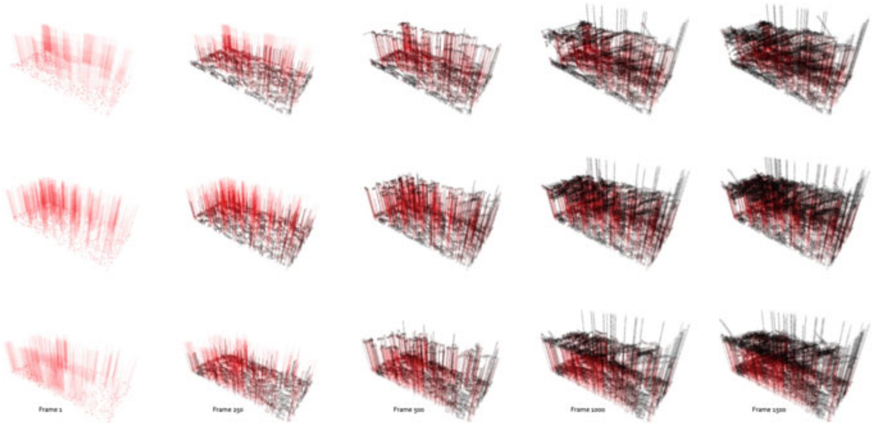

Fig. 6. Proposed CA neighborhood interaction model from a CA seed adding separation, alignment and cohesion on a 3d environment

that sense, the CA generated lattice structure works as a communication media between seeds and collective memory and crowd Intelligence simultaneously.

4 Conclusions: CA as Bottom-Up Architecture with Memory

Memory has more than only a unique dimension from which the architectural design can grow towards a new dimension, less deterministic and more responsive to new possible scenarios. As a design tool for projects, this concept can bring coherence to the broken link between design and the built environment in the fine grain of the neighborhood, learning how the geometrical structure can learn from the urban data field as useful generative information for the system, in a coherent way.

Learning from natural systems, it is possible to understand how the shapes are arranged in the environment, being adaptive and highly scalable due to efficient subcomponents as fundamental building blocks of growing (primary forms). Applying geometrical rules from these previous steps has been possible to develop small structures to read, learn and create strong support for the design project. Using points and lines as a geometrical base is suitable to merge the worlds of nature and science with architecture and design, making it necessary to review our design protocols, changing the classic disciplinary conception to a new model of design, with fewer preconceptions and more perceptions (capturing and analyzing all the available dimensions of information from our project site).

Every new step in the growing process can increase the result definition, adding frames to project development. This is the key in the system simulation: more time = more quality = more accuracy. On the other hand, it is impossible to accelerate the final solution only by increasing the number of growing seeds in the space because more elements can exponentially increase the number of interactions in the site as an evolutive mainframe, distorting the final solution.

CA can generate a trace of its existence based on the activation and deactivation of the discrete system that grows, like a footprint in the affected area of intervention, improving a "stigmergic operation" in the field, conditioning the following steps in the collaborative growing of this basal structure. This cooperative way of space construction was and is one of the essential elements in this research; without this, the ever-increasing by the collective action of seeds could be unfeasible, without historical registry of expansion or contractions in the whole system, and at the end with less or no coordination between cells as a choreography of termites building a termite mound. As pseudo-natural forms, this way of design has memory in itself, storing its historical evolution, feeding the following steps on this system, conditioning the use of rules and paths inside the project development, focused on design data field conditions instead of only one unique result.

Maps of movement and evolution are the hidden information of our eyes, which can be switched from negative to positive as a structural result (points as articulations and lines as connections), being a final link between virtuality (the hidden) and reality (the visible). From the built environment reality, points, lines and shapes are how the city infrastructure dialogues with itself and the environment in a broad sense. A field condition ruled more than only translated by these simple geometrical elements. Finally, we can understand that memory and Intelligence are working together in a distributed way, instead just only as a concentrated model with one input and a set of possible outputs, like models based on machine learning that are working similarly to natural neural systems and the way biologic neurons convey information by integrating incoming inputs. CA can be referred to as self-Intelligence organization, to the overall coherence of the generative structure, displaying patterns and behaviors in a decentralized, non-controlled system, in which complex systems are constructed using essential pieces with just local interactions as a structural analogue, building Intelligence in the process.

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