

Exploration of Non-Local Cellular Automata and Emergent Particle Behaviors

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Abstract. This exploratory paper investigates the emergent behaviors of a novel class of non-local, stochastic Cellular Automata (CA). The structural evolution is driven by a specialized execution rule, animating the system forward. We demonstrate that interactions between these automata termed Nagas - including collisions, yield complex dynamic behaviors such as absorption path deflection. Notably, the underlying structures exhibit natural analogues to physical properties such as velocity, momentum, and elastic collisions. This class of systems demonstrates compelling emergent properties, enabling directional propagation at variable angles and velocities while strictly conserving both total cell counts and specific cell types, even during interactions.

1 Introduction

By investigating information-preserving CAs under non-standard rulesets, we identify a distinct structural class presented in this paper: the Non-Adjacent Gyration Automata (NAGA). The NAGA framework is of particular interest because it admits a direct mapping to classical physical concepts, such as momentum $\mathbf{p}$, velocity $\mathbf{v}$, and mass m . Within this model, we recover both Euclidean propagation trajectories and variable velocities up to a fundamental upper limit w_{max} .

Consequently, we investigate whether this structure exhibits more advanced particle-like behaviors, including energy conservation, momentum transfer, and elastic collisions. Distinct from traditional models, cells that activate in this framework do not directly modify the states of immediate spatial neighbors. Instead, they execute functions on adjacent elements within connected strings of cells, establishing a functional (non-local) adjacency between the head and tail.

It can be argued that these mechanics fall outside the scope of classical CAs, because these are usually defined to have unitary evolution and local neighborhoods. In addition, most work in CAs are often restricted to one or two dimensions. This CA violates these conventions in three key ways:

1. It is explicitly defined in a three-dimensional (3D) discrete space.
2. It utilizes non-local evolution dynamics.
3. It incorporates stochastic evolution where the chronological execution order influences the outcome.

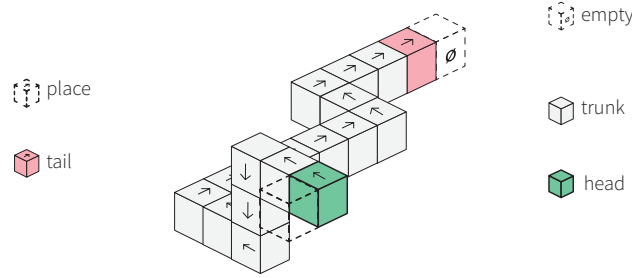


Fig. 1: A Naga pattern

$$\leftarrow \leftarrow \downarrow \downarrow \leftarrow \leftarrow \nearrow \nearrow \nearrow \nearrow \nearrow \nearrow \leftarrow \leftarrow \nearrow \nearrow \nearrow \nearrow$$

$$\vec{p} = [0_{\rightarrow}, 0_{\uparrow}, 10_{\nearrow}, 6_{\leftarrow}, 2_{\downarrow}, 0_{\swarrow}]$$

Analyzing such frameworks provides a bottom-up complement to top-down searches for CAs capable of generating quantum phenomena, such as the network approaches by Wolfram and Gorard [1]. Following foundational work by 't Feynman [2] and t'Hooft [3], constructing valid representations of quantum mechanics using cellular frameworks is theoretically viable. This alignment with quantum mechanics is further supported by formalizations of quantum lattice gases and cellular automata, which demonstrate how particle translation emerges from discrete unitary rules [4]. However, this paradigm relies on the premise that underlying discrete automata can natively generate the phenomenology described by the quantum wave function.

The empirical violation of Bell's inequalities [5] has implications for the viability of local classical CAs as generators of quantum-like behaviors. This is because local hidden-variable theories are ruled out following Bells work on the EPR paradox [5]. Consequently, the conventional notion that cellular automata frameworks are required to observe strict locality if they are to serve as viable physical models is fundamentally unwarranted. In fact, it can be argued that at the fundamental scale, the exact opposite is the case.

If such underlying non-local CA models exist, it is methodologically sound to limit the scope, and establish fundamental correspondences to macroscopic physics first, including stable trajectories, periodicity, particle-like translation, and strict conservation laws.

2 Method

The Naga is defined in a discrete universe modeled as a cubic crystal lattice where each cell possesses at least 3 bits of information. We define a NAGA structure across a contiguous sequence of adjacent cells. The localized information within each cell is utilized to express unit vectors. Structurally, a Naga (see Fig. 1) consists of a chain of unit vectors positioned such that each vector points directly into the succeeding cell in the sequence, with the exception of the terminal node.

We define the boundaries of the structure as follows:

- A **head** is a cell with no parent (i.e., no other cell points into it).
- A **tail** is a cell that points into an empty cell, denoted by $\emptyset$.

¹ Let the total number of connected cells within a given string be represented by the integer N . Let the six cardinal directions of the lattice be represented by the spatial symbols $\rightarrow, \uparrow, \nearrow, \leftarrow, \downarrow, \swarrow$, and let the empty state be denoted by $\emptyset$. Each individual cell within this lattice is termed a *Moykle*.

Definition 1 (Moykle Alphabet). *The Moykle alphabet Σ consists of 7 distinct symbols:*

$$\Sigma = \{\emptyset, \rightarrow, \leftarrow, \uparrow, \downarrow, \nearrow, \swarrow\} \quad (1)$$

These symbols represent the empty state ($\emptyset$) and the six directional unit vectors pointing to immediate spatial neighbors. Specifically, the unit vectors are mapped as $\rightarrow = [1, 0, 0]$, $\leftarrow = [-1, 0, 0]$, $\uparrow = [0, 1, 0]$, $\downarrow = [0, -1, 0]$, $\nearrow = [0, 0, 1]$, and $\swarrow = [0, 0, -1]$.

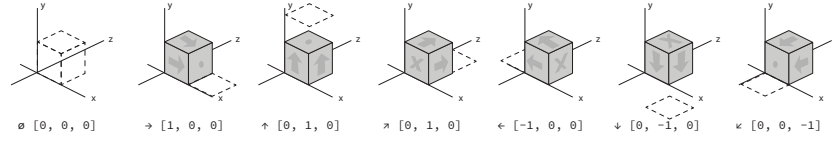


Fig. 2: The seven distinct moykle symbols and their arrow-adjacent position (dotted)

2.1 Six-component vector-notation

A Naga can be summarized in six component form, by associating the variables a, b, c, d, e, f as counts of the each unit vectors type $\rightarrow, \uparrow, \nearrow, \leftarrow, \downarrow, \swarrow$, respectively.

We have that

$$\check{p} = [a_{\rightarrow}, b_{\uparrow}, c_{\nearrow}, d_{\leftarrow}, e_{\downarrow}, f_{\swarrow}], \quad a, b, c, d, e, f \in \mathbb{Z}^+ \quad (2)$$

The evolution function depends on a non-local update rule that operates on the head cells only. The evolution rule follows the arrows until and identifies the tail. It then swaps the tail with the position adjacent to head, such that the tail cell becomes the new head cell.

The head and the tail are typically not adjacent cells. Hence, it can be argued, that the Naga is not an unitary CA, but rather a kind of stochastic, CA-like dynamical system. It should be noted however, that the model remains local in a strict sense - each cell can only call a function on its adjacent cells.

¹ Following this definition, it is notable that a single, isolated cell satisfies both criteria, acting simultaneously as a head and a tail.

2.2 Velocity

The maximum speed of a propagating Naga is naively one where it never backtracks, see Fig 3a. This requires that there are no opposing unit vectors in the chain, e.g. no $\leftarrow$ and $\rightarrow$ present in the same string. The velocity of such a Naga is equal to 1 in natural units. For a counter example, see illustration of a partially backtracking Naga, see 3b. This must have an velocity less than 1 because part of its cycles are used to move back and forth along the same dimension. It follows that the average velocity vector of the Naga as a whole can be expressed as a fraction of 1.

$$\mathbf{w} = \left[\frac{a-c}{N}, \frac{b-d}{N}, \frac{c-d}{N} \right] \quad (3)$$

The scalar velocity of this NAGA is the length of this vector.

2.3 Momentum

From classical physics we take the notion of particle characterized by a position $\mathbf{x}$, mass m and a velocity vector $\mathbf{v}$, and the classical identity of momentum $\mathbf{v}m = \mathbf{p}$

By (4), we let mass m be related to N , and obtain directly a momentum analogue (5) from the NAGA cell composition.

$$m \propto N \quad (4)$$

$$\mathbf{p} = \mathbf{v}m = \mathbf{w}N \quad (5)$$

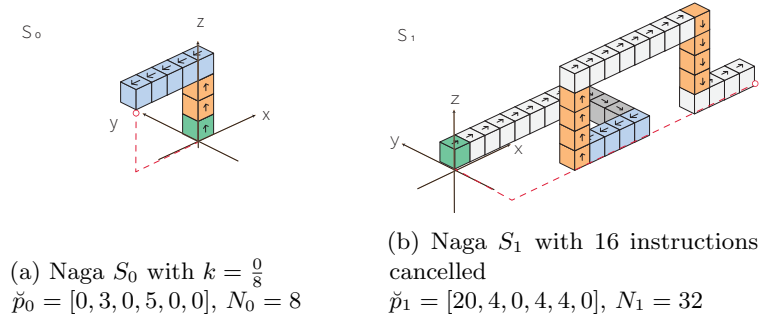


Fig. 3: Nagas with and without cancelled instructions

2.4 Simulation Methodology

Using custom simulation software [6], multiple NAGA structures were initialized on trajectories designed to induce collisions. The system was then evolved forward to record and analyze the resulting behavioral dynamics. By systematically varying the initial spatial configurations and orientations, we cataloged the complete spectrum of interaction modalities and classified their outcomes.

3 Results and Analysis

3.1 Conservation of Cell Counts

Empirical data demonstrate that the total counts of each distinct Moykle type within the lattice remain strictly constant throughout the evolution. No cell types are created or destroyed during spatial translation or structural reconfiguration.

3.2 Standard Collision Dynamics

Standard interactions occur when a head Moykle becomes spatially adjacent to a Moykle that does not point directly into it, creating an intersection termed a *junction*. These junctions resolve over finite simulation steps through a process where the two Nagas exchange constituent Moykles. Typically, the impinging Naga is either partially or fully absorbed into the receptive structure.

As a consequence of this exchange, both participating Nagas alter their trajectories. Because the aggregate counts of each directional Moykle type are invariant, the total system momentum remains strictly conserved:

$$\mathbf{p}_{\text{total}} = \mathbf{p}_0 + \mathbf{p}_1 = \text{invariant} \quad (6)$$

3.3 Kinetic halting and structural tangles

Extended simulations reveal that collisions can occasionally cause total kinetic halting. This occurs when colliding Nagas form interleaved topological *interaction tangles* that are cyclic, or sufficiently constrained to resolved by the execution ruleset.

Once formed, these static tangles remain deadlocked until an external Naga collides with the structure, providing the perturbation required to unfreeze the system. Statistically, these configurations are rare; the steady-state population of frozen tangles does not accumulate over time, remaining a negligible proportion relative to propagating Nagas.

3.4 Reviewing interaction stages

We first examine how two interacting Nagas, denoted as S_0 and S_1 exchange Moykles. The Moykle action results in two important sequences of interaction, which is depicted in several key steps across multiple figures.

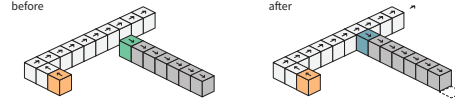
1. **Ordinary propagation:** Two Nagas move independently, Fig 4a (before).
2. **Junction Formation:** Two Naga enter a junction configuration, shown in Figure 4a (after). This setup is critical for initiating the interaction process.
3. **Semaphore swap:** This typically redirects the arrow at the junction into the impinging Naga S_0 , (Figure 4b).
4. **Transplanting the tail:** The next step involves placing a non-local swap of the transplanted tail from one Naga to another, depicted in Figure 4c. (Note that the two are functionally connected). This action prepares the system for the absorption phase.
5. **Absorption:** After these preliminary steps, direct absorption may occur, where one Naga absorbs Moykles originally belonging to the other, as illustrated in Figure 4d.
6. **Semaphore reversal** The absorption process often becomes halted by a semaphore reversal (Figure 5a).
7. **Placing of the transplanted Tail:** Before returning to ordinary propagation for S_1 , the transplanted tail is promoted as a new head for S_1 (Fig 5c).

The system tends to oscillate between absorbing (Fig. 4a) and ordinary propagation states (5c), with tail transplantation (4c) and semaphore swaps (4b) as intermediate steps. Because state transitions follow the activation of a HEAD moykle, the chronological ordering of these activations dictates the outcome. Consequently, activation between S_0 and S_1 yields a stochastically evolving system with inherently random interaction results. Outside of interactions, NAGA behaviour remains predictable, realizing a well-defined time-averaged velocity given by (3). While random execution also triggers complex separation and emission dynamics, analyzing these behaviors is planned for future papers.

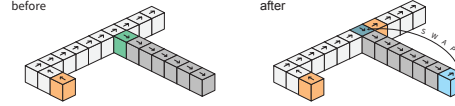
4 Discussion

The NAGA framework exhibits distinct particle-like characteristics, including variable trajectories, structural periodicity, and multi-body interactions. Although cells lack strict spatial adjacency, the terminal head and tail nodes establish a *functional adjacency* via the recursive evolution rule. This non-local coupling enables the discrete structures to traverse the lattice through a pseudo-local loop reminiscent of a discrete soliton wave [7]. The framework simultaneously realizes several interconnected physical properties:

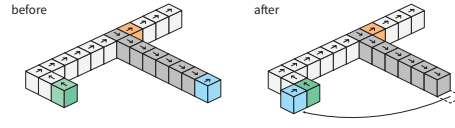
1. **Structural Periodicity:** Each individual Naga configuration exhibits a deterministic, oscillatory cycle during its translational phase.
2. **Quantized Velocity:** The propagation rate through the lattice is bounded and reproducible, yielding a consistent velocity profile directly governed by the internal vector composition.
3. **Directional Approximation:** Trajectories span discrete spatial vectors composed by the summation of the constituent unit vectors. Longer chains (large N) yield a finer directional resolution[8]



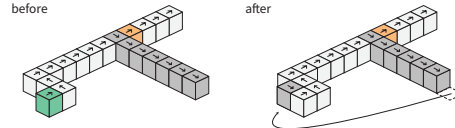
(a) S_0 (bold) impinges on S_1 , and forms a junction



(b) S_0 (bold) produces a semaphore swap operation on junction S_1



(c) S_1 follows into S_0 , but takes the transplanted tail, ready for direct absorption



(d) S_1 is now directly absorbing Moykles S_0 each time the S_1 head is selected

Fig. 4: Process of absorption from junction formation

4. **Momentum Analogy:** By mapping the total cell count N as proportional to classical inertial mass, we formalize a mathematical analogue for physical momentum. As demonstrated, this quantity remains invariant under standard, non-entangled interactions, effectively mimicking elastic collision dynamics.

The NAGA framework offers an interesting foundation for discrete physical modeling. Future work will expand upon these emergent properties by conducting rigorous investigations into multi-particle scattering dynamics and the evolutionary mechanics of frozen states.

References

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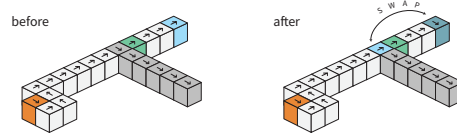
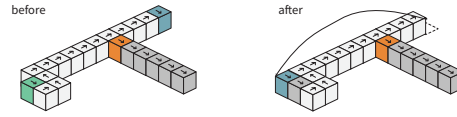
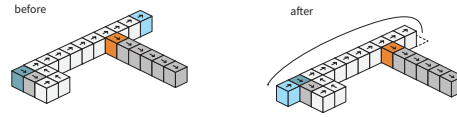
(a) $S_0 S_1$, Semaphore reversal(b) S_1 Takes the transplanted tail with S_1 (c) Ordinary propagation, S_1 takes from own tail

Fig. 5: Semaphore flickering : Mixing behaviour with absorption

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