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Collisions and their Catenations: Ultimately Periodic Tilings of the Plane

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Abstract. Motivated by the study of cellular automata algorithmic and dynamics, we investigate an extension of ultimately periodic words to two-dimensional infinite words: collisions. A natural composition operation on tilings leads to a catenation operation on collisions. By existence of aperiodic tile sets, ultimately periodic tilings of the plane cannot generate all possible tilings but exhibit some useful properties of their one-dimensional counterparts: ultimately periodic tilings are recursive, very regular, and tiling constraints are easy to preserve by catenation. We show that, for a given catenation scheme of finitely many collisions, the generated set of collisions is semi-linear.

Introduction

The theory of regular languages, sets of one-dimensional sequences of letters sharing some regularities, has been well studied since the sixties. Finite state machines [17], regular languages [13], computing devices with bounded memory, monadic second-order logic [4]: various point of views lead to a same robust notion of regular languages. The concept extends to infinite words and various other one-dimensional structures. Unfortunately, when considering two-dimensional words – partial mappings from the plane $\mathbb{Z}^2$ to a finite alphabet – such a robust common object fails to emerge: automata on the plane, picture languages, second-order logic, all lead to different notions of regular languages [8]. A first difficulty arises from the definition of a finite word: should it be any partial mapping with a finite support? Should it be rectangles filled with letters? Should it be any mapping with a connected support for some particular connexity notion? A second difficulty arises from the complexity of two-dimensional patterns: in the simplest case of uniform local constraints, *i.e. tilings*, knowing whether a given finite pattern is a factor of a valid tiling (of the whole plane) is already undecidable [1].

In the present paper, we investigate a particular family of recursive tilings of the plane endowed with a catenation operation. Our definition of an ultimately periodic tiling, a *collision*, is inspired by geometrical considerations on one-dimensional cellular automata space-time diagrams and tilings. It can be thought of as an extension of the notion of ultimately periodic bi-infinite words to two-dimensional words. These objects provide a convenient tool to describe synchronization problems in cellular automata algorithmic.

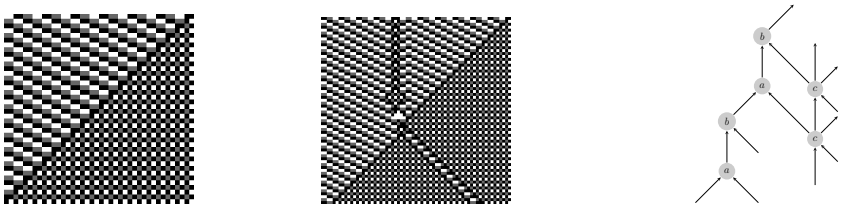
One-dimensional cellular automata [12] are dynamical systems whose configurations consist of bi-infinite words on a given finite alphabet. The system evolves by applying uniformly and synchronously a locally defined transition rule. The value at each position, or *cell*, of a configuration only depends on the values of the cells on its neighborhood at the

previous time step. To discuss the dynamics or to describe algorithmic constructions, it is often convenient to consider space-time diagrams rather than configurations. A space-time diagram is a drawing of a particular orbit of the system: configurations are depicted one on top of the other, from bottom to top, by successively applying the transition rule, as depicted on Fig. 1. This representation permits to draw away the time-line and discuss the structure of emerging two-dimensional patterns. Formally, this is equivalent to consider tilings of half the plane with a special kind of local constraint, oriented by the time-line.

Time goes from bottom to top. Each letter is represented by a different color.

Fig. 1. space-time diagram of a one-dimensional cellular automaton

Let us give first an informal overview of what collisions are and where they come from. An ultimately periodic configuration consists of two infinite periodic words separated by a finite non-periodic word. As transitions of cellular automata are locally defined, the image of an ultimately periodic configuration is an ultimately periodic configuration such that: for each periodic part, the period in the image divides the period in the preimage ; for the non-periodic part, it can only grow by a finite size depending on the local rule. If, by iterating the transition rule of the cellular automaton, the size of the non-periodic part of the configurations remains bounded, then the orbit of the ultimately periodic configuration is, up to a translation, ultimately periodic. When considering this ultimately periodic behavior from the space-time diagram point of view, one can see some kind of *particle*: a localized structure moving with a rational slope in a periodic *background* environment, as depicted on Fig. 2a.



(a) particle (b) collision (c) network of collisions

Fig. 2. particles and collisions generated by ultimately periodic configurations

As particles are ultimately periodic configurations, one can construct more complicated configurations by putting particles side by side, ensuring that the non-periodic parts are far enough from each other, and that the periodic parts of two particles put side by side are the same and well aligned. If the non-periodic part of several particles (two or more) becomes near enough in the orbit, complex interactions might occur. If the interaction is localized in both space and time, as depicted on Fig. 2b, this interaction is called a *collision*.

Particles and collisions provide a convenient tool in the study of cellular automata. When constructing two-dimensional cellular automata, like in historical constructions of Von Neumann [19] and Codd [5], particles are a convenient way to convey quanta of information from place to place. The most well known example of particle is certainly the glider of the Game of Life used by Conway *and al* to embed computation inside the Game of Life

[2] by using particular behavior of glider collisions. When using one-dimensional cellular automata to recognize languages or to compute functions, a classical tool is the notion of signal introduced by Fischer [7] and later developed by Mazoyer and Terrier [15, 16]: signals and their interactions are simple kinds of particles and collisions. Particles appears even in the classification of cellular automata dynamics: in its classification [20], Wolfram identifies what he calls class 4 cellular automata where *"(...) localized structures are produced which on their own are fairly simple, but these structures move around and interact with each other in very complicated ways. (...)"* A first study of particles interaction was proposed by Boccara *and al* [3], latter followed by Crutchfield *and al* [11]: these works focus on particles and bounding the number of possible collisions they can produce. Finally, the proof by Cook of the universality of rule 110 [6] is a typical construction involving a huge number of particles and collisions: once the gadgets and the simulation are described, the main part of the proof consists of proving that particles are well synchronized and that collisions occur exactly as described in the simulation.

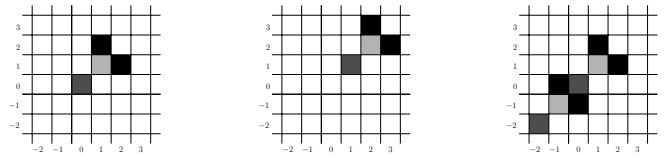
When dealing with space-time diagrams consisting of only particles and collisions, a second object is often used: a planar map describing the collisions and their interactions. When identifying particles and collisions in space-time diagrams, in the style of Boccara *and al* [3], one builds the planar map to give a compact description of the diagram, as depicted on Fig. 2(c). When describing algorithmic computation, in the style of Fischer [7], one describes a family of planar maps as a scheme of the produced space-time diagrams.

The aim of the present paper is to define particles and collisions, describe how collisions can be catenated, introduce collisions schemes as planar maps and discuss the construction of finite catenations from collisions schemes. All the necessary material is defined in section 1 followed by basic catenation of tilings in section 2. Collisions and their catenations are formally introduced in section 3. The main result on catenation is presented in section 4.

1 Definitions

In the remaining of this paper, every discussion occurs in the *two-dimensional plane* $\mathbb{Z}^2$ partially colored with the letters of a given finite alphabet Σ. A *pattern* is a subset of $\mathbb{Z}^2$. A *cell* c of a given pattern P is an element $c \in P$. A *vector* is an element of the group $(\mathbb{Z}^2, +)$ of translations in the plane. A *coloring* $\mathcal{C}$ is a partial map from $\mathbb{Z}^2$ to Σ. The *support* of a *coloring* $\mathcal{C}$ is denoted by $\mathrm{Sup}(\mathcal{C})$, its restriction to a pattern P is denoted by $\mathcal{C}_{|P}$.

The *translation* $u \cdot \mathcal{C}$ of a coloring $\mathcal{C}$ by a vector u is the coloring with support $\mathrm{Sup}(\mathcal{C}) + u$ such that, for all $z \in \mathrm{Sup}(\mathcal{C})$, it holds $(u \cdot \mathcal{C})(z + u) = \mathcal{C}(z)$. The *disjoint union* $\mathcal{C} \oplus \mathcal{C}'$ of two colorings $\mathcal{C}$ and $\mathcal{C}'$ is the coloring with support $\mathrm{Sup}(\mathcal{C}) \cup \mathrm{Sup}(\mathcal{C}')$ such that, for all $z \in \mathrm{Sup}(\mathcal{C})$, it holds $\mathcal{C} \oplus \mathcal{C}'(z) = \mathcal{C}(z)$ and for all $z \in \mathrm{Sup}(\mathcal{C}')$, it holds $\mathcal{C} \oplus \mathcal{C}'(z) = \mathcal{C}'(z)$. Colorings and their operations are depicted on Fig. 3.



(a) a coloring $\mathcal{C}$ (b) $\binom{1}{1} \cdot \mathcal{C}$ (c) $\mathcal{C} \oplus \binom{-2}{-2} \cdot \mathcal{C}$

Fig. 3. colorings, translations and disjoint unions

A *tiling constraint* is a pair (V, Υ) where V is a finite pattern and Υ is a subset of Σ^V. A coloring $\mathcal{C}$ *satisfies* a tiling constraint (V, Υ) if for each vector $u \in \mathbb{Z}^2$ such that V is a subset of $\mathrm{Sup}(u \cdot \mathcal{C})$, it holds $(u \cdot \mathcal{C})_{|V} \in \Upsilon$. For now on we fix a tiling constraint (V, Υ). A *tiling* is a coloring with support $\mathbb{Z}^2$ that satisfies the tiling constraint.

In the following, for geometrical considerations, we will implicitly use variations of discrete forms of the Jordan curve theorem [14]. Two points $\binom{x}{y}, \binom{x'}{y'} \in \mathbb{Z}^2$ are *4-connected* if $\binom{|x-x'|}{|y-y'|} \in \left\{\binom{1}{0}, \binom{0}{1}\right\}$, *8-connected* if $\binom{|x-x'|}{|y-y'|} \in \left\{\binom{1}{0}, \binom{0}{1}, \binom{1}{1}\right\}$. A pattern P is *4-connected*, *resp. 8-connected*, if for each pair of point $z, z' \in P$, there exists a 4-connected, *resp.* 8-connected, path of points of P from z to z'. The discrete Jordan curve theorem states that any non empty 4-connected closed path separates the plane into two 8-connected patterns, the interior and exterior of the path. More generally, a *frontier* is a 4-connected pattern separating the plane into n 8-connected patterns, its *borders*.

2 Catenation of tilings

Let (V, Υ) be a tiling constraint and C a set of colorings satisfying this constraint. To generate tilings by catenating colorings in C, the idea is to construct a patchwork of colorings by cutting portions of coloring and glue them together so that tiling constraints are preserved. A simple patchwork of 2 tilings is depicted on Fig. 4.

(a) coloring ■ (b) coloring ■ (c) blueprint (d) patchwork

Fig. 4. a patchwork

Definition 1. *A* patchwork *is a tiling $\mathcal{T}_\phi$ defined for each $z \in \mathbb{Z}^2$ by $\mathcal{T}_\phi(z) = \phi(z)(z)$ where $\phi : \mathbb{Z}^2 \to C$ is the* blueprint *of the patchwork such that:*

1. $\forall \mathcal{C} \in C, \quad \partial\phi^{-1}(\mathcal{C}) \subseteq \mathrm{Sup}(\mathcal{C})$;
2. $\forall z \in \mathbb{Z}^2, \forall v \in V, \quad \phi(z)(z+v) = \phi(z+v)(z+v)$.

Patchworks provide a convenient way to combinatorially generate tilings from a set of valid colorings without knowing explicitly the tiling constraint: it is sufficient to know a superset of the tiling neighborhood V and to cut colorings on a big enough boundary containing the same letters.

Topology is a classical tool of symbolic dynamics [10], tilings being exactly the shifts of finite type for two-dimensional words. The set of colorings is endowed with the so called Cantor topology: the product of the discrete topology on $\Sigma \cup \{\perp\}$ where $\perp$ denotes undefined color. This topology is compatible with the following distance on colorings: $d(\mathcal{C}, \mathcal{C}') = 2^{-\min\left\{|z|, \mathcal{C}(z) \neq \mathcal{C}'(z)\right\}}$. Let $\mathcal{O}_\mathcal{C}$ be the set of colorings $\mathcal{C}'$ such that $\mathcal{C}'_{|\mathrm{Sup}(\mathcal{C})} = \mathcal{C}_{|\mathrm{Sup}(\mathcal{C})}$. The set of $\mathcal{O}_\mathcal{C}$ for colorings $\mathcal{C}$ with a finite support is a base of clopen sets for the given compact perfect topology.

Proposition 1. *The set of patchworks over C is a compact set. Furthermore, it contains the tilings of the closure of C.*

Proof. Let $\mathcal{T}_i$ be a sequence of patchworks over C converging to a limit tiling $\mathcal{T}$. Consider the blueprints ϕ_i of these patchworks. For each cell $z \in \mathbb{Z}^2$, let v_z be the element $(-z \cdot \mathcal{T})_{|V}$ of Υ. Let $\phi(z)$ be any $\phi_i(z)$ such that $(-z \cdot \phi_i(z))_{|V} = v_z$ – such a $\phi_i(z)$ always exists by definition of patchworks as $\mathcal{T}_i$ converges to $\mathcal{T}$. The map ϕ is a blueprint for $\mathcal{T}$.

Let $\mathcal{C}_i$ be a sequence of colorings in C converging to a limit tiling $\mathcal{T}$. For each $\mathcal{C}_i$, let P_i be the largest pattern, for inclusion, such that $\mathcal{C}_{i|P_i} = \mathcal{T}_{|P_i}$. As the sequence $\mathcal{C}_i$ converges to $\mathcal{T}$, the sequence P_i converges to $\mathbb{Z}^2$. Without loss of generality, consider that P_i is an increasing sequence of patterns. For each i let $\delta(i)$ be the smallest j such that $\partial P_i \subseteq P_j$. Consider $P'_n = P_{\delta^n(1)}$, an increasing subsequence of P_i. Construct a blueprint ϕ as follows: for all $z \in \mathbb{Z}^2$, let $\phi(z) = P'_{\min\{n|z \in P'_n\}}$. By construction, this blueprint is valid and its patchwork is $\mathcal{T}$. ■

Corollary 1. *Let $\mathcal{O}_i$ be a base of open sets of colorings and C be a set of colorings containing at least one element of each $\mathcal{O}_i$. The set of patchworks over C is the whole set of tilings.* ■

In particular, the set of tiling constraints Υ, viewed as colorings, generates the whole set of tilings. The larger set of colorings with finite support generates the whole set of tilings. But this approach is heterogeneous: we combine colorings to obtain tilings. Can we restrict ourselves to combinations of tilings? More precisely, given a tiling constraint, can we recursively construct a recursive family of tilings T such that the set of patchworks over T is the whole family of tilings?

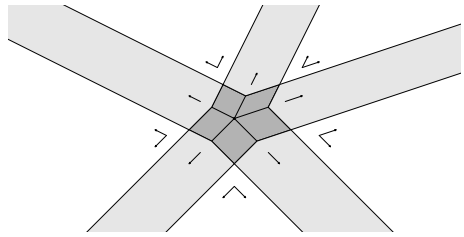
In the case of one-dimensional tilings, replacing $\mathbb{Z}^2$ by $\mathbb{Z}$, it is straightforward that the set of ultimately periodic tilings generates the whole set of tilings: the set of ultimately periodic tilings is a dense set – from any tiling $\mathcal{T}$ and any finite pattern P, one can construct an ultimately periodic tiling $\mathcal{T}'$ such that $\mathcal{T}_{|P} = \mathcal{T}'_{|P}$. In the case of two-dimensional tilings, due to the undecidability of the tiling problem [1, 18], there exists no such family. This result prohibits us to obtain a recursive set of tilings whose closure under catenation give us the whole set of tilings. Therefore, in the rest of the paper, we search for simplicity rather than being exhaustive.

3 Ultimately periodic tilings

Bi-periodic tilings are among the most regular ones and correspond to the idea of a *background* for cellular automata: a tiling $\mathfrak{B}$ with two non-collinear periodicity vectors u and v such that $\mathfrak{B} = u \cdot \mathfrak{B} = v \cdot \mathfrak{B}$. As backgrounds are objects of dimension 2, if one wants to mix several backgrounds in a same tiling, the interface between two background is of dimension 1. The most regular kind of interface corresponds to the idea of a *particle*: a tiling $\mathfrak{P}$ with two non-co-linear vectors, the period u of the particle such that $\mathfrak{P} = u \cdot \mathfrak{P}$ and the period v of its backgrounds such that for all position $z \in \mathbb{Z}^2$, the extracted one-dimensional word $(\mathfrak{P}(z + vi))_{i \in \mathbb{Z}}$ is ultimately periodic. Of course, several particles might meet on the plane, leading to objects of dimension 0 that correspond to the idea of a *collision*. In this paper, an ultimately periodic tiling of the plane is such a collision.

Let $\lhd_v(u, u')$ denote the angular portion of the plane, on the right hand side of u, starting in position $v \in \mathbb{Z}^2$ and delimited by the vectors $u, u' \in \mathbb{Z}^2$. Formally, one might geometrically define a collision as follows (and depicted on Fig. 5):

Definition 2. *A* collision *is a tiling $\mathfrak{C}$ for which there exists an integer k and a finite cyclic sequence of n vectors $(u_i) \in \left(\mathbb{Z}^2\right)^{\mathbb{Z}_n}$ such that, for all $i \in \mathbb{Z}_n$, $\mathfrak{C}$ is u_i-periodic in z, i.e. $\mathfrak{C}(z) = \mathfrak{C}(z + u_i)$, for all positions z inside $\lhd_{ku_i}(u_{i-1}, u_{i+1})$.*

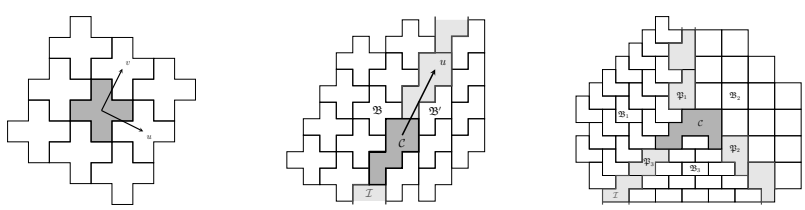


$k = 2$
$u_0 = \binom{1}{2}$
$u_1 = \binom{3}{1}$
$u_2 = \binom{2}{-2}$
$u_3 = \binom{-2}{-2}$
$u_4 = \binom{-2}{1}$

Fig. 5. defining collisions through vectors

Although it corresponds to intuition, this definition made it difficult to effectively use collisions in constructions since it does not identify components of the collision. To overcome this problem, we introduce *constructive* versions of collisions. Ideas behind such definitions is that all elements can be represented with a finite description. A background is entirely determined by two non-collinear vectors of periodicity u and v and by a coloring of finite support $\mathcal{C}$ that tiles the plane along u and v (i.e.$\bigoplus_{i,j\in\mathbb{Z}^2}(iu+jv)\cdot\mathcal{C}$ is a tiling) (see Fig. 6) . Such a triple $(\mathcal{C}, u, v)$ is called *background representation.*

The same way, in a particle, the uni-periodic part can be characterised by a vector u and a coloring with finite support $\mathcal{C}$ which repetition along u ($\mathcal{I} = \bigoplus_{k\in\mathbb{Z}} ku\cdot\mathcal{C}$) is a frontier with two borders (L and R). The rest of particle can be described using two backgrounds $\mathfrak{B}$ and $\mathfrak{B}'$. The resulting coloring $\mathfrak{P} = \mathfrak{B}_{|L} \oplus \mathcal{I} \oplus \mathfrak{B}'_{|R}$ is require to be a tiling. Furthermore, we require to have a condition ensuring that the different portion have some common "safety zone". This is done by adding the constraint that the function : $\phi : z \to \begin{cases} \mathfrak{P} & \text{if } z \in \mathrm{Sup}(I) \\ \mathfrak{B} & \text{if } z \in L \\ \mathfrak{B}' & \text{if } z \in R \end{cases}$ is the blueprint of a patchwork. Such a tuple $(\mathfrak{B}, \mathcal{C}, u, \mathfrak{B}')$ is called *particle representation.*



(a) a background (b) a particle (c) a collision

Fig. 6. principle of construction

For collisions, the idea is basically the same (see Fig. 6) , the characterisation is based on a coloring with finite support $\mathcal{C}$ for the non-periodic part and a finite list of particles. Each particle defines a half-line starting form the center of the collision. The support of all the particle and the center must form a star and each consecutive pair of particle must have a common background to fill the space between them. Some safety zone is also required as in particle. This is formalised in the following definition:

Definition 3. *A* collision representation *is a pair $(\mathcal{C}, L)$ where $\mathcal{C}$ is a finite pattern, L is a finite sequence of n particles $\mathfrak{P}_i = (\mathfrak{B}_i, \mathcal{C}_i, u_i, \mathfrak{B}'_i)$, satisfying:*

1. $\forall i \in \mathbb{Z}_n, \quad \mathfrak{B}'_i = \mathfrak{B}_{i+1}$;
2. *the support of $\mathcal{I} = \mathcal{C} \oplus \bigoplus_{i\in\mathbb{Z}_n, k\in\mathbb{N}} ku_i \cdot \mathcal{C}_i$ is a frontier with n borders;*

3. *For all $i \in \mathbb{Z}_n$, the support of $\mathcal{C} \oplus \bigoplus_{k\in\mathbb{N}} (ku_i \cdot \mathcal{C}_i \oplus ku_{i+1} \cdot \mathcal{C}_{i+1})$ if a frontier with two borders: let P_i be the border on the right of $\mathfrak{P}_i$;*
4. $\mathfrak{C} = \mathcal{I} \oplus \bigoplus_i \mathfrak{B}_{i|P_i}$ *is a tiling;*
5. *the function* $\phi : z \to \begin{cases} \mathfrak{C} & \text{if } z \in \mathrm{Sup}(\mathcal{C}) \\ \mathfrak{P}_i & \text{if } z \in \mathrm{Sup}(\bigoplus_{k\in\mathbb{N}} ku_i \cdot \mathcal{C}_i) \\ \mathfrak{B}_i & \text{if } z \in P_i \end{cases}$ *is the blueprint of a patchwork.*

The set $\mathrm{Sup}(\mathcal{C})$ is called *perturbation* of the collision and $\mathrm{Sup}(\bigoplus_{k\in\mathbb{N}} ku_i \cdot \mathcal{C}_i)$ are called *perturbation* of the particle P_i.

The constructive definitions of particles, backgrounds and collisions provides us with a finite representation that allows us to recursively manipulate them. Contrary to intuition, representation are not invariant by translation. This seems unavoidable since we want to have means of expressing the relative position between two such representation. In the rest of the paper, we will always assume that background, particles and collisions are given by a representation.

4 Finite catenations

A blueprint of finitely many collisions might produce a tiling which is not a collision, however if the blueprint of the patchwork consists of finitely many 8-connected components, the patchwork is a collision. Using representations of collisions, a more regular family of patchworks can be defined: a catenation induces a patchwork combining collisions by binding pairs of similar particles as depicted on Fig. 2.

To "bind" collisions using particles, we need two identical particles facing each other such that the gap between them correspond to a integer number of particles n. Two particles $\mathfrak{P} = (\mathfrak{B}, \mathcal{C}, u, \mathfrak{B}')$ and $\tilde{\mathfrak{P}} = (\tilde{\mathfrak{B}}, \tilde{\mathcal{C}}, \tilde{u}, \tilde{\mathfrak{B}}')$ form a *n-binding* if $\tilde{u} = -u$ (particles are facing each other), $\tilde{\mathcal{C}} = (n-1)u \cdot \mathcal{C}$ (they have the same finite pattern and gap is n repetitions) , $\tilde{\mathfrak{B}} = (n-1)u \cdot \mathfrak{B}'$, $\tilde{\mathfrak{B}}' = (n-1)u \cdot \mathfrak{B}$ (backgrounds are the same). The set $\bigoplus_{0<i<n-1} iu \cdot \mathcal{C}$ is called the *perturbation* of the n-binding.

Since we want to get rid of positions, we introduce the *potential n-binding*. The idea is that given two collisions and one particle for each collisions, the particles $\mathfrak{P}_1$ and $\mathfrak{P}_2$ form a *potential n-binding* if up to a translation z, the to particles form an n-binding (i.e. $\mathfrak{P}_1$ and $z \cdot \mathfrak{P}_2$ form a n-binding). One can remark in case of potential n-binding, the translation vector z is unique.

Now the idea is that we can use potential n-binding to construct patchworks since background is bi-periodic and does not cause heavy harm for checking properties on it. The description needs to have collisions as points and particles as lines. Particles can be half-infinite (if they are not part of potential n-binding) or link two collisions. Since we work in the plane, it is sound to require that the constructed element is planar and that the order of particles is compatible with the collisions. At last, we add a connected condition to avoid problem with free parts of the map. This leads to the following definition:

Definition 4. *A* catenation *is a connected planar map where :*

- *vertices are labeled by collisions;*
- *edges are potentially semi infinite;*
- *edges extremities are labeled by particles;*
- *edges order in a vertex is compatible with the order on particles in the corresponding collision.*

– *finite edges (of extremities $\mathfrak{P}_1$ and $\mathfrak{P}_2$) are labeled with an integer n such that $\mathfrak{P}_1$ and $\mathfrak{P}_2$ form a potential n-binding.*

At this point, we want to transform the catenation into a patchwork. For this, let us first study some necessary conditions. Since we deal with a planar map, it is possible to define faces as elements of the dual of catenation. To transform a catenation into a patchwork, it is necessary that every face can be transformed into a patchwork. Since we have potential n_i-bindings, the translation induced between two consecutive collisions is fixed. Since the sequence of collisions in a face is cyclic, it is sound to require that the sequence of corresponding translation sum up to zero when cycling. This will be the first condition. Now, with this condition, it is possible to assign (up to a global constant) a translation to every collision such that all edges are n_i-bindings. With those objects, the basic idea is to construct a patchwork that corresponds to each collision, particle or n_i-binding on its perturbation. This implies that all perturbations does not enforce contradictions. One easy way to get rid of this risk is just to require that all perturbations are distinct (this will be our second condition). If these conditions are met then we speak of *valid* catenation.

Proposition 2. *It is possible to associate a patchwork to every valid catenation.*

Proof. To prove this result, we shall give a potential blueprint and he show that it satisfies the conditions. First of all, the condition on null translation after a round on every faces induce a unique set of translation (up to a constant) for every collision in the map since the map is connected. At this point, let us consider the collisions with those translations.

The second conditions ensure that perturbations of collisions, bindings and particles are disjoint. Thus it is possible to define a blueprint linking any point of such a perturbation to the corresponding collision, particle or binding. Let us now study the points that are not mapped. Since the map is planar and particle (and also bindings) are isolating, every left point belongs to one unique face. On this face, the associated background with particles or collision or bindings present is unique (bindings ensure that two consecutive collisions have the same and collisions ensure this for consecutive particles and bindings). So we map those points to the corresponding background.

The last point is to show that the constructed blueprint does really satisfy the properties for patchwork. The first condition on definition is trivial since the used valid colorations are tilings. Let us go now to the second and main point.

For this last part, let us study the different cases. For example, if we are in a collision $\mathfrak{C}$ perturbation. If the neighborhood is also in $\mathfrak{C}$ perturbation or in perturbation of binding, particle belonging to $\mathfrak{C}$ or even of background with this property, then the neighborhood is by definition equal to the original one of a collision. the only difficult case is when in the neighborhood, there is a perturbation originated from another element. For example let us suppose this elements is in the perturbation from $\mathfrak{C}'$. In this case, in $\mathfrak{C}$ we have in these points some backgrounds or particles. But since perturbations do not overlap, we are in the border of $\mathfrak{C}'$. As we have requested in our constructive version representation to be patchworks, the border of $\mathfrak{C}'$ does correspond to the value of backgrounds or particles present in $\mathfrak{C}'$. By definition of our catenations, the backgrounds and particles are the same so elements of $\mathfrak{C}'$ are the same of those in $\mathfrak{C}$.

The same arguments do also apply for other cases thus ending the proof. ■

At this point, the result looks quite promising because it links with formal conditions how catenations can be turned into patchworks. However, catenations are indeed a bit too precise. When dealing with behavior, one does not want to give explicitly the number

of repetitions of the particles. Thus we introduce the notion of *pre-binding* that indicates that two particles can form a binding without specifying the number of repetitions. The pre-binding condition can be easily formalised as for potential n-binding. Thus we can introduce another planar map when value for repetitions are stripped and potential n-binding condition is replaced by pre-binding. Such a map is called *catenation scheme*. Such object do really correspond to our intuitive vision of behavior.

The catenation scheme seems to be the good "high-level" element to easily describe the wanted behavior. One good question is to know how to go back from catenation scheme to patchwork. Coincidentally, we will use catenation to go back. To go from a catenation scheme to a catenation, one needs to put an integer on each finite edge. Such application is called *affectation* of a catenation scheme. Such an affectation is said to be *valid* if the corresponding catenation is valid. Thus one easy way to prove that a catenation scheme can be converted into a patchwork is to show that it contains admit a valid affectation. In the case of finite catenation (i.e. with a finite number of vertrices), it is possible to obtain a strong result:

Theorem 1. *The set of valid affectation of a finite catenation is a recursive semi-linear set (i.e. a finite union of linear sets)*

This result is very interesting since its allows a way back. Starting with a set of particles and collisions, one can manipulate them abstractly and study possible finite catenation scheme. After that, this theorem provides a tool to directly show whether or not such scheme correspond to real tilings.

Proof. To prove the main theorem, we will show that being a valid affectation of finite catenation scheme can be expressed with a formula in Presburger arithmetic (i.e first order logic on integer with addition and comparison). Since the set of solution of formula in such arithmetic is a recursive semi-linear set [9] this will conclude the proof. One can note that the construction of the solution is explicit even if the complexity is non-elementary.

In our formula, the number of repetitions of each finite edge will correspond to free variables. let us call them $r_1, \ldots, r_n$. Since the conditions for valid catenation are for each face, the global formula F will consists on the conjunction of an elementary formula for each face : $F = \wedge_{f\text{face}} F_f$. For each face, let us look at the two conditions. First one (going back to the same point after a turn around the face) can be easily expressed: the translation induced by a particle i is just r_i times the vector of repetition of the particle u_i (just note that the direction of the particles is chosen in the face) which is a known constant. For the translation induced by collision ϵ_c they are know constant. So the formula is on the form $F_{f,1} = \Sigma_{i\text{particles in the face}} u_i r_i + \Sigma_{c\text{collisions}} \epsilon_c = \binom{0}{0}$. For the second condition (non overlap of perturbation) it can be expressed with the conjunction that any pair of points of different perturbations are distinct. In the case of collision perturbation, it is trivial since there is only a finite (and known) number of perturbation points. For bindings, it is more difficult since the set of points can be expressed with a universal quantifier with the following remark, the set of points in the binding's perturbation correspond to the set of points of the particle perturbation $\mathrm{Sup}(\mathcal{C}_i)$ (a finite number) for every integer n multiple of the vector of repetition u_i which is between 0 and the number of repetition r_i. thus the formula is on the form: $\forall x, 0 < x < r_i \Rightarrow \wedge_{p \in \mathrm{Sup}(\mathcal{C}_i)} p + u_i r_i \neq z$ where z are points for the other considered perturbation. The same applies for free particles (just omit the upper bound in the comparison).

With this, we have sow how to construct the Presburger formula which conclude the proof. ■

This theorem allows us to clear the case of finite catenations. In cellular automata algorithmic, constructions might involve infinite number of catenations. One perspective of future work is to give formalism to those infinite catenation allowing to have similar results. As a similar theorem for any infinite catenation seems very unlikely, two main approaches are either to restrict the set of catenation considered or to recognize only a subset of valid catenations.

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A Appendix

In this appendix, we provide a full example of use of the framework presented in this paper. To do this, we show how to construct an automaton with a specific behavior (in our example, calculate one step of the Syracuse sequence) and prove that the constructed automaton really works.

A.1 Constructing the automaton

The idea is to describe the desired behavior of our automaton using geometrical signals and then to implement a cellular automaton rule with this behavior. Suppose that we have encoded the current value of the sequence in a gap between to vertical signals (see Fig. 7). Suppose also that the start of the step is given by a full-speed left-going signal coming from left. This signal cross the right boundary in α and arrive in the left one in β. Now, let us distinguish both cases: in the odd case, we send a full speed right going signal from β and a signal with slope 1/2 from α. Their intersection will mark 3 time the initial distance. In the even case, we send at the same time a 1/3 slope signal from β and a full speed signal which reflex again the left boundary. Those two signal will intersect at half the initial size. In our sketch, we also add some other signals for cleaning purpose or convenience. Note that our solution is nor unique nor optimal but merely an interesting example.

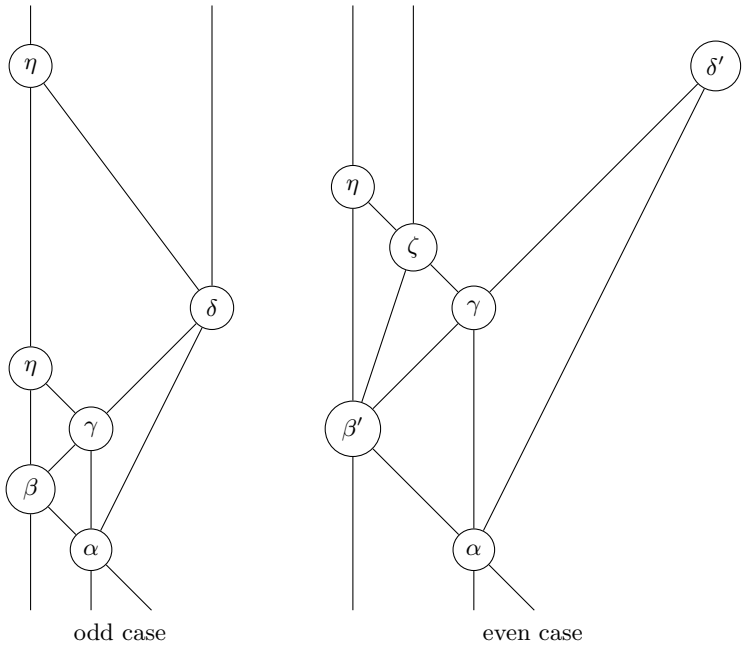


Fig. 7. Computing one step of the Syracuse sequence with geometric signals

From the geometric figure, we want to construct an automaton with 1 background, 7 particles and 8 collisions. The rest of the section is devoted to construct a rule exhibiting these objects. The choice of transitions is detailed in Fig 8a for each elements, the set of used transition (that do not map on white) are given along an extract of the object space-time diagram (Fig. 8b).

The chosen background is just uniformly white. For full speed or vertical particles, the chosen implementation is nearly always to take a supplementary state for each particle. One can note that particle c is made of two different altering states. These states allows to remember the parity of the length. For other slopes, the particle is constructed by using several states for alternating staying and advancing at the correct rate. One can note that particles g also contains a bit of information in its repetition (as particle c).

A.2 Catenations

For this automaton, we shall look at the two catenation scheme induced by the geometric signal approach (see Fig. 7). The faces present in these schemes are depicted on Fig. 8d. In this section, we shall give the detailed study of face F_1.

First of all, let us express the fact that we are going back to the same point after a turn around the face. For this face, we have three bindings. The oriented repetition axes of these particles are: $u_a = \binom{0}{-1}$, $u_c = \binom{-2}{2}$ and $u_e = \binom{1}{1}$. Each of the three collision induce a translation between the two present particles. Here, we have $\epsilon^{\alpha}_{a,c} = \binom{-2}{-3}$ $\epsilon^{\beta}_{c,e} = \binom{-1}{5}$ and $\epsilon^{\gamma}_{e,a} = \binom{3}{0}$. The resulting equation is obtained by summing up all the contributions and requesting a null sum:

$$F_0 : (r_a - 1)u_a + \epsilon^{\alpha}_{a,c} + (r_c - 1)u_c + \epsilon^{\beta}_{c,e} + (r_e - 1)u_e + \epsilon^{\gamma}_{e,a} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Once this is done, it is possible to associate to each collision a translation t_i which only depends linearly on the number of repetition of particles inside bindings. Then it is time for expressing the fact that perturbations are distinct. The formula are different along the considered elements. Simplest one are describing the non-overlap of collisions perturbations. For example, the equation for perturbations of α and β is

$$F_{\alpha,\beta} : \bigwedge_{x \in \mathrm{Sup}(t_\alpha \cdot \mathcal{C}_\alpha)} \bigwedge_{y \in \mathrm{Sup}(t_\beta \cdot \mathcal{C}_\beta)} x \neq y$$

. The same can be done between collisions and bindings supports. For example, the equation between perturbation of α and e is on the form:

$$F_{\alpha,e} : \bigwedge_{x \in \mathrm{Sup}(t_\alpha \cdot \mathcal{C}_\alpha)} \forall p \in \mathbb{N}, 0 \leq p < r_e \Rightarrow \bigwedge_{y \in \mathrm{Sup}(\mathcal{C}_e)} x \neq y + pu_e$$

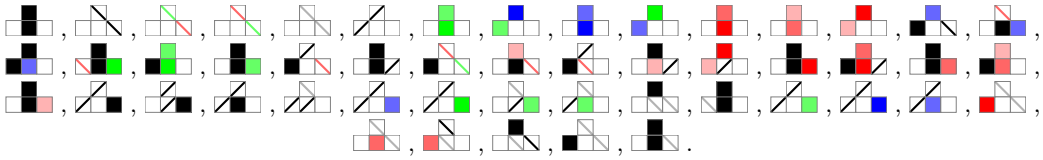
The same formula can be expressed in the case of two bindings.

The equation for the face is made by doing the conjunction of all the previous formula:

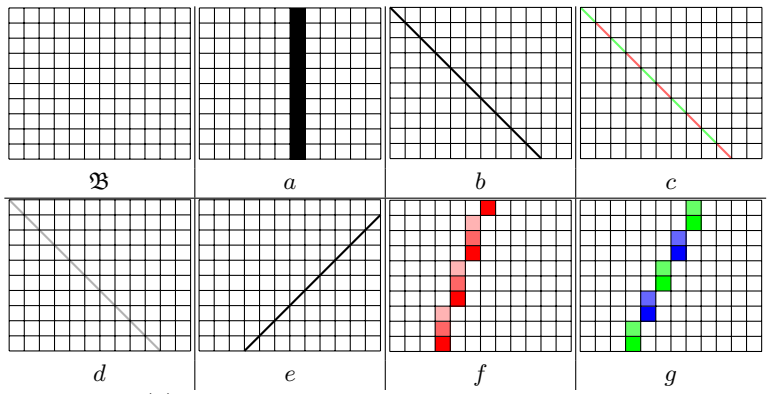
$$F : F_0 \wedge \bigwedge_{x,y \in \{\alpha,\beta,\gamma,a,e,c\}, x \neq y} F_{x,y}$$

At this point, one can use quantifier elimination and find the set of values for r_a, r_e and r_c that satisfy the formula. We obtain that the set of solution is on the form :

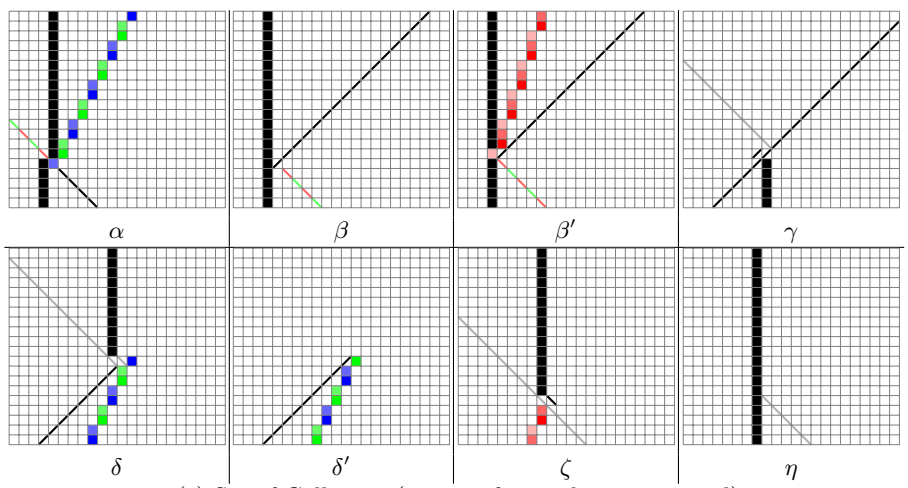
$$\begin{pmatrix} n_c \\ n_e \\ n_a \end{pmatrix} \in \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + \mathbb{N} \begin{pmatrix} 1 \\ 2 \\ 4 \end{pmatrix}$$



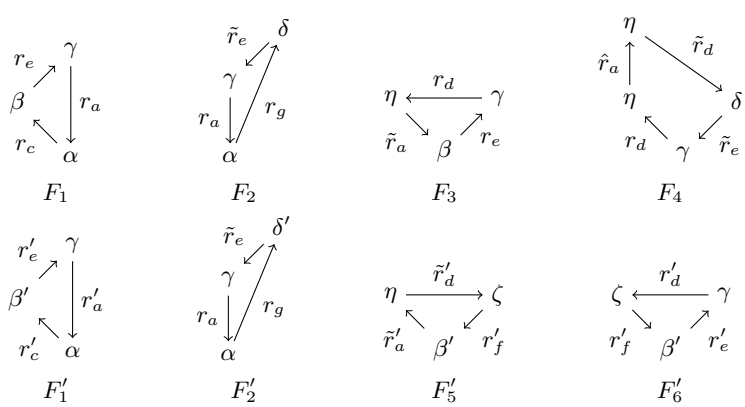
(a) Set of constraints: all non defined behavior maps on □



(b) The background and used set of particles



(c) Set of Collisions (names of particles are omitted)



(d) Faces present in catenation schemes

Fig. 8. Elements of the automaton

$\begin{pmatrix}0\\0\\1\end{pmatrix}+\mathbb{N}\begin{pmatrix}1\\2\\4\end{pmatrix}$	$\begin{pmatrix}1\\2\\1\end{pmatrix}+\mathbb{N}\begin{pmatrix}2\\2\\1\end{pmatrix}$	$\begin{pmatrix}6\\2\\0\end{pmatrix}+\mathbb{N}\begin{pmatrix}2\\1\\1\end{pmatrix}$	$\begin{pmatrix}0\\6\\2\\0\end{pmatrix}+\mathbb{N}\begin{pmatrix}0\\2\\1\\1\end{pmatrix}+\mathbb{N}\begin{pmatrix}1\\0\\1\\0\end{pmatrix}$
$F_1(r_c, r_e, r_a)$	$F_2(r_a, \tilde{r}_e, r_g)$	$F_3(\tilde{r}_a, r_d, r_e)$	$F_4(r_d, \hat{r}_a, \tilde{r}_d, \tilde{r}_e)$
$\begin{pmatrix}0\\0\\4\end{pmatrix}+\mathbb{N}\begin{pmatrix}1\\2\\4\end{pmatrix}$	$\begin{pmatrix}0\\1\\1\end{pmatrix}+\mathbb{N}\begin{pmatrix}2\\2\\1\end{pmatrix}$	$\begin{pmatrix}11\\0\\2\end{pmatrix}+\mathbb{N}\begin{pmatrix}4\\1\\1\end{pmatrix}$	$\begin{pmatrix}0\\0\\0\end{pmatrix}+\mathbb{N}\begin{pmatrix}1\\1\\2\end{pmatrix}$
$F_1'(r_c', r_e', r_a')$	$F_2'(r_a', \tilde{r}_e', r_g')$	$F_3'(\tilde{r}_a', \tilde{r}_d', r_f')$	$F_4'(r_f', r_d', r_e)$

Fig. 9. Validity set for faces

The same can be done with all other faces. The results are given in Fig. 9. In our simple case, all solutions are just linear set and half-infinite faces do not bring any further constraints so they were omitted in this tabular. At this point, one want to study the set of validity for the whole scheme. One can note that it correspond to make the synchronized product of the set of validity of the faces. The resulting set found is depicted in Fig. 10. Note that since all repetitions numbers must be positive, the even case has implicit requirement $x > 1$.

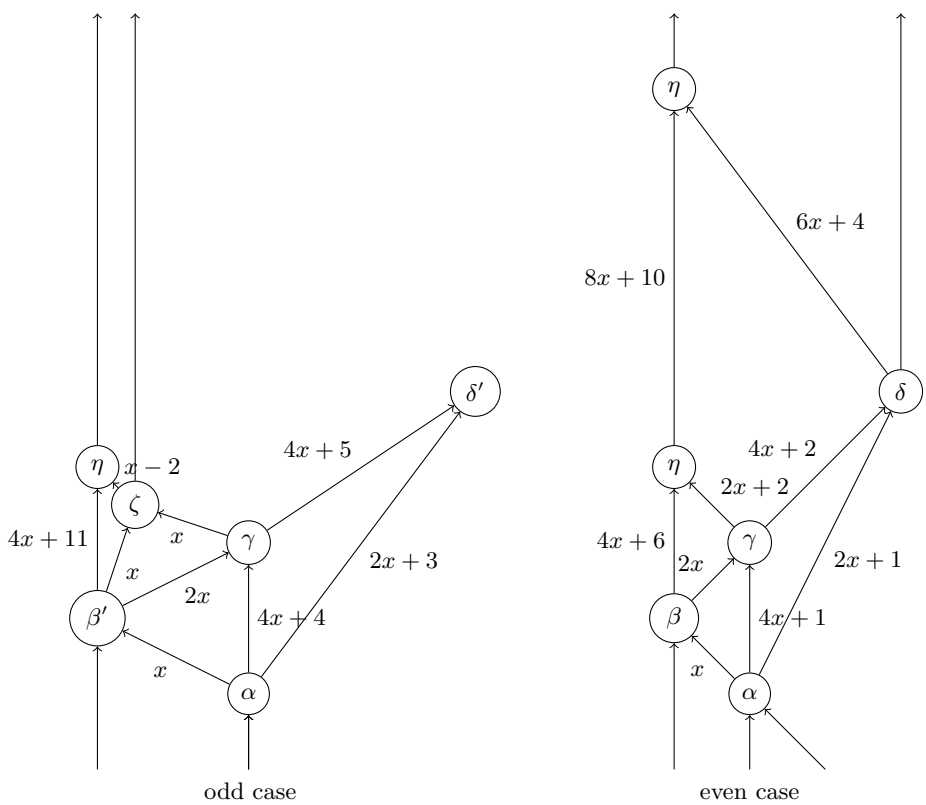


Fig. 10. Solution of the faces

A.3 Behavior

The previous result give us an idea of possible behavior and when they occur. To finish our construction and proof, we need to relate the number of particles to the encode value. In the odd case, the fact that $r_c = x$ induce a distance of $2x+3$ between the two particles a whereas the value $\tilde{r}_d = 6x + 4$ correspond to a distance of $6x + 10$. In the odd case, $r'_c = x$ correspond to an input of $2x + 4$ and $\tilde{r}_d = x - 2$ to a distance of $x + 2$. Thus we have proved that our automaton can compute one step of the Syracuse sequence (for sufficiently large values of input).

The main advantage of this method of construction is that the proof does follow directly the method of construction and does not require to make study the local details (since they are hidden in the resolution of the validity set). Thus making the proof easier to follow.