Avancées récentes sur des questions issues des pavages du plan par translation d'une tuile

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Travail fait en collaboration avec Ariane, Alexandre et Srečko

Outline

1. Introduction
   - Discrete Figures
   - Tilings
   - Beauquier and Nivat
   - Hexagonal and Square Tiles
   - A conjecture of Brlek, Dulucq, Fédou and Provençal, 2007
   - A conjecture of Provençal and Vuillon, 2008
2. (Idea of the) Proof of the first conjecture
3. (Idea of the) Proof of the second conjecture
4. Open problems

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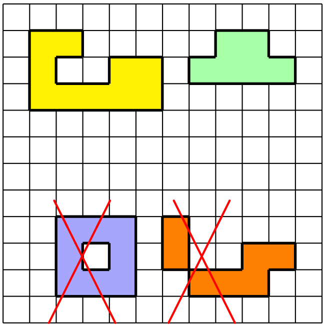
Discrete Figures and Polyominoes

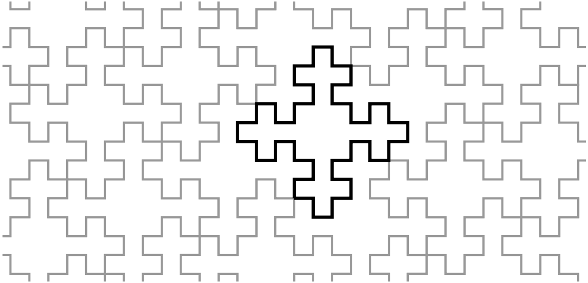
- Discrete plane : $\mathbb{Z}^2$
- **Definition** : A polyomino is a finite, 4-connected subset of the plane, without holes.



The Tiling by Translation Problem

Let P be a polyomino. We say that

- P tiles the plane if there exists a set T of non-overlapping translated copies of P that covers all the plane.
- P is called a tile if it tiles the plane.



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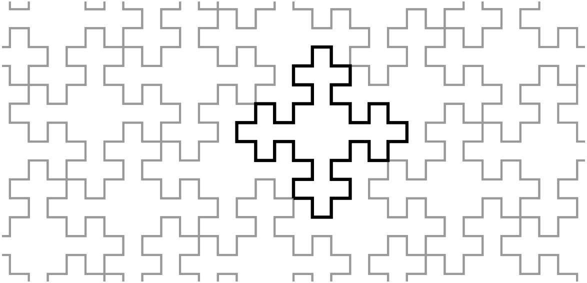
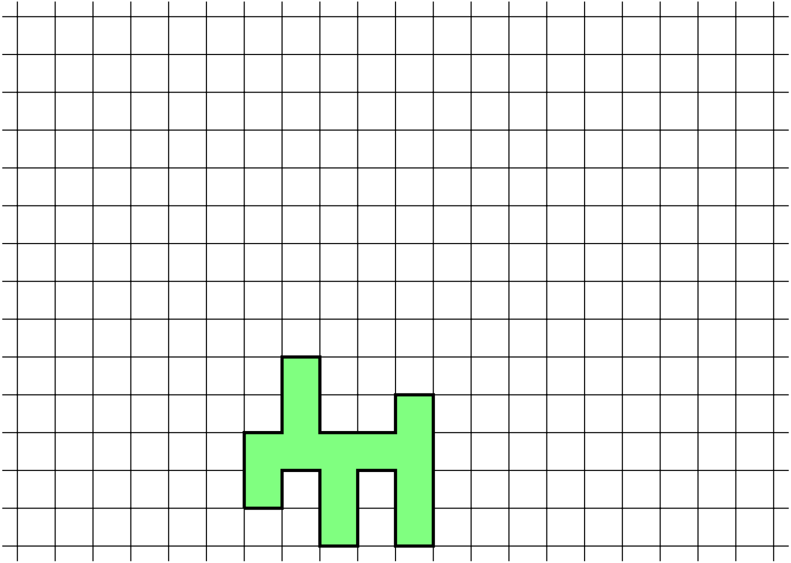
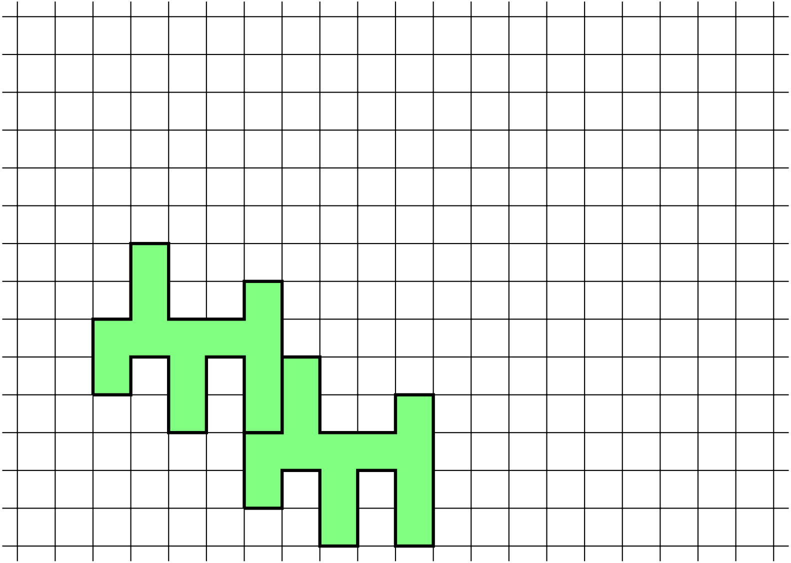
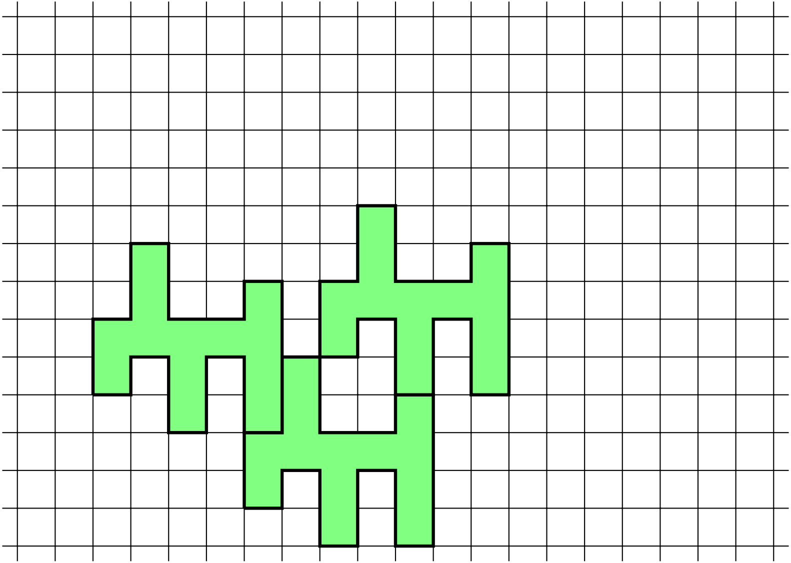


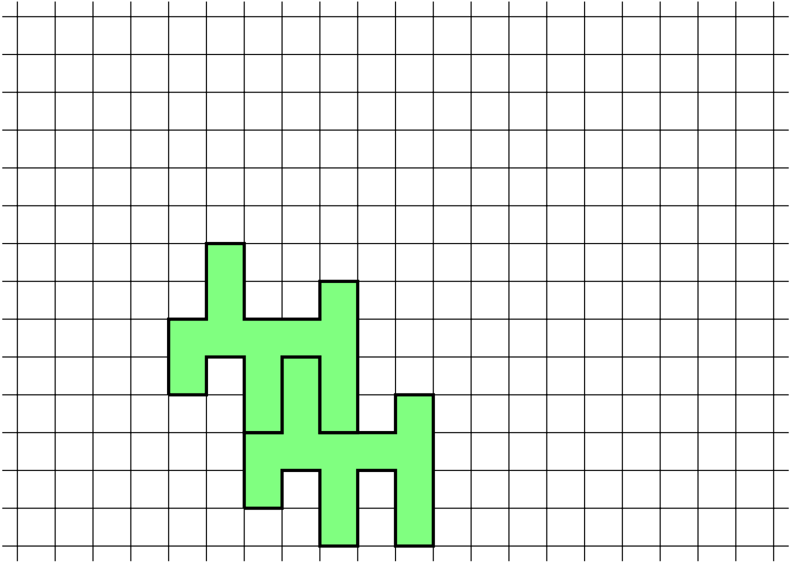
Problem

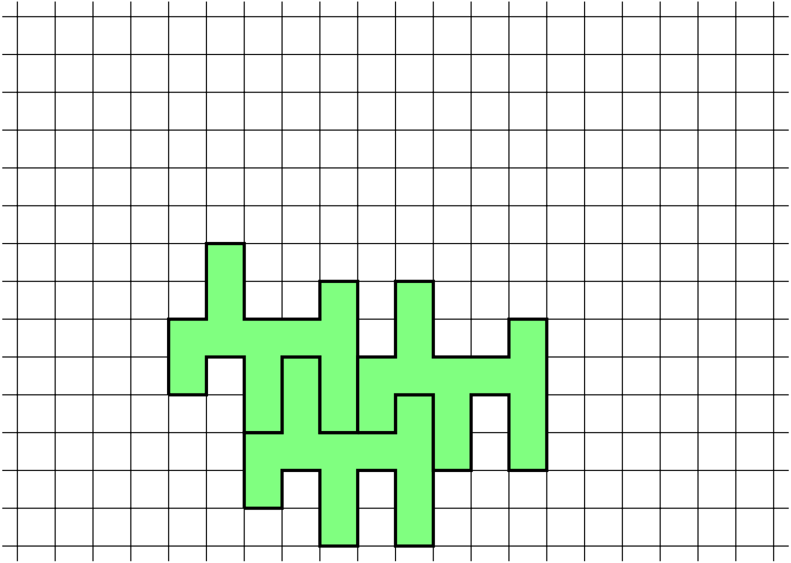
Does a given polyomino P tile the plane ?

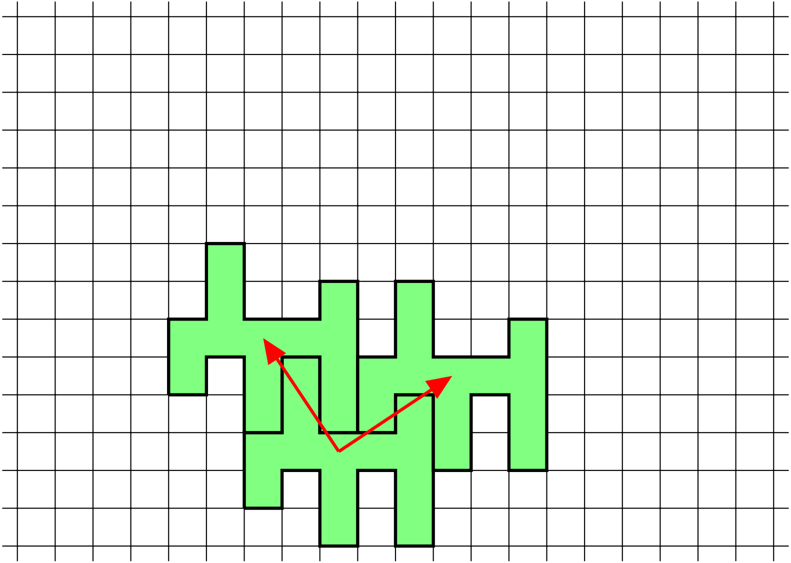


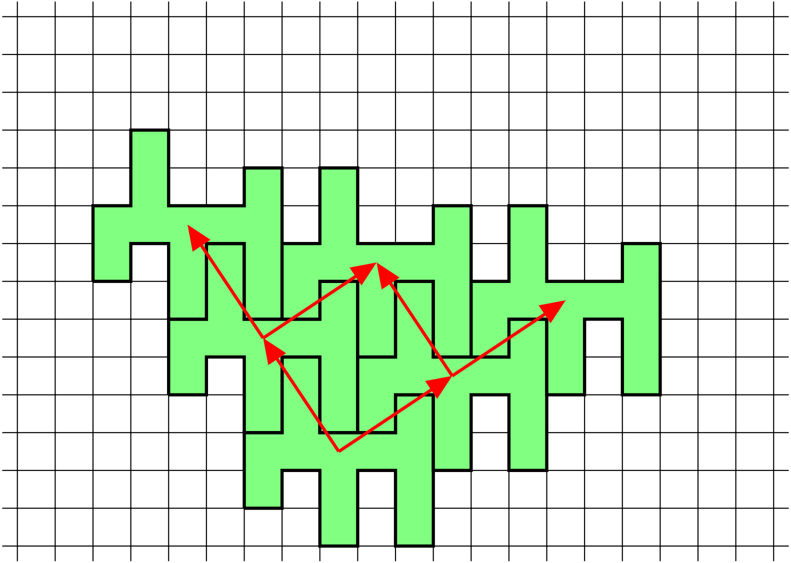


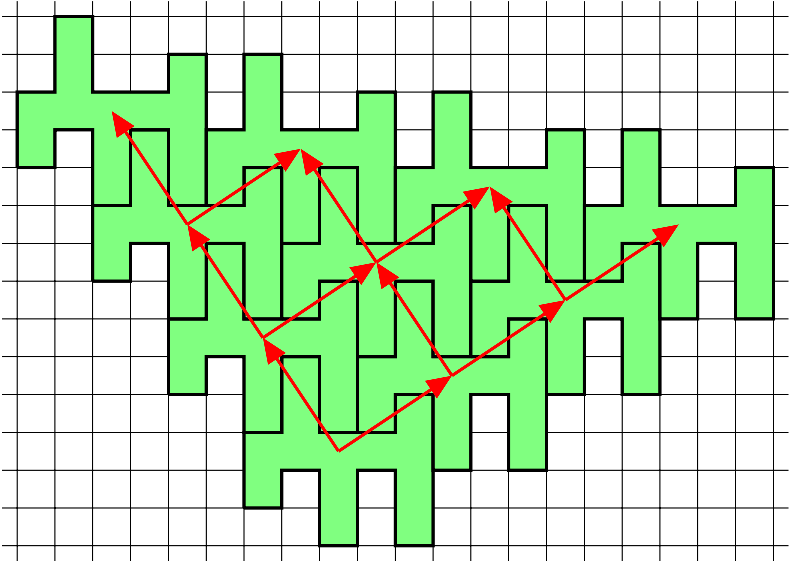


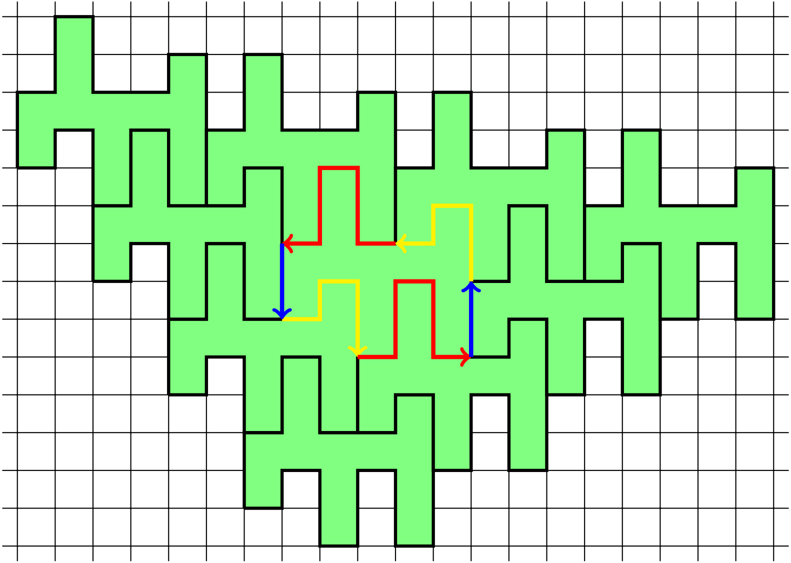






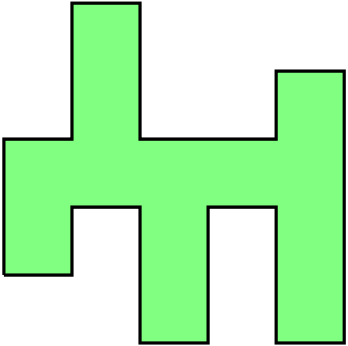


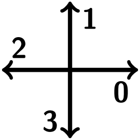




Freeman Chain Code

$$\Sigma = \mathbb{Z}_4 = \{\mathbf{0}, \mathbf{1}, \mathbf{2}, \mathbf{3}\}$$





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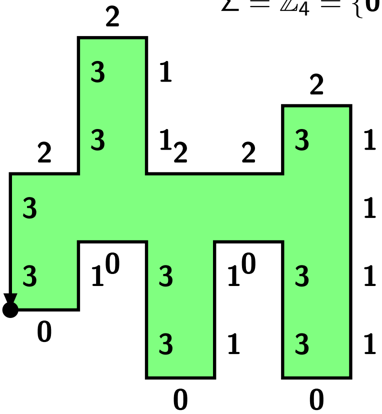

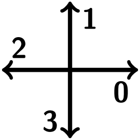

$w = \mathbf{01033011033011112322112332 33}$

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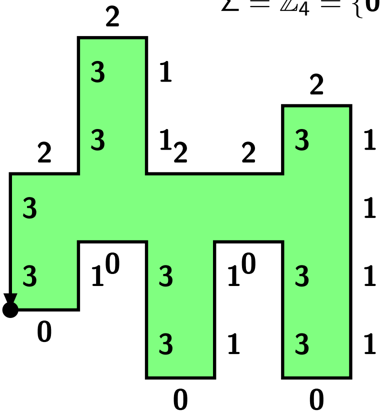

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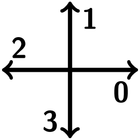

Any conjugate w' of w codes the same polyomino.

w and w' are conjugate if there exist $u, v \in \Sigma^*$ such that $w = uv$ and $w' = vu$. We write $w \equiv_{|u|} w'$.

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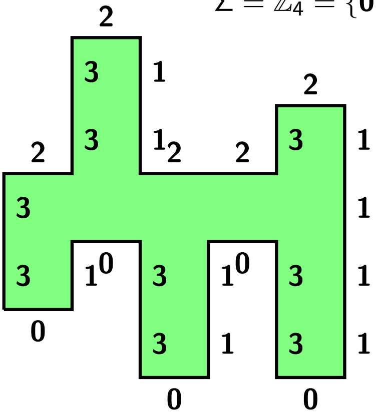

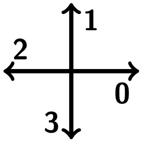

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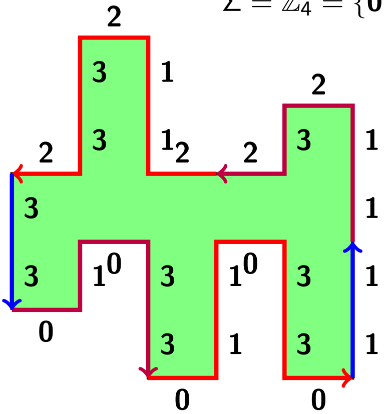

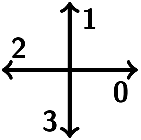

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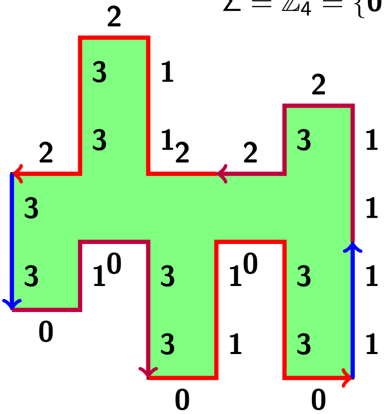

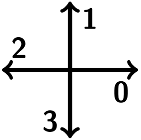

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$[w] \equiv$

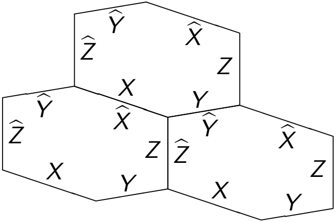
01033	0110330	11	11232	2112332	33
X	Y	Z	$\widehat{X}$	$\widehat{Y}$	$\widehat{Z}$


Characterization : A polyomino P tiles the plane if and only if there exist $X, Y, Z \in \Sigma^*$ such that $[w] \equiv XYZ\widehat{X}\widehat{Y}\widehat{Z}$.

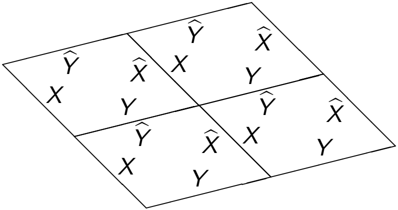
$X = \mathbf{0\;0\;1\;0\;3\;0\;1}$

$\widehat{X} = \mathbf{3\;2\;1\;2\;3\;2\;2}$

hexagon tiles



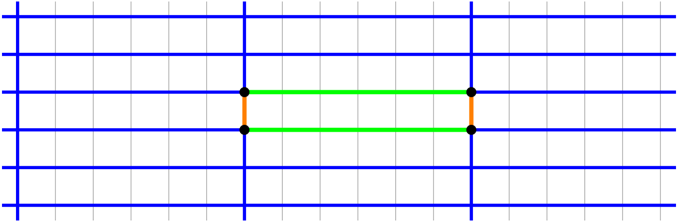
square tiles



Maurits Cornelis Escher (1898-1972). Hexagonal tiling. Square tiling.

Hexagonal Tilings

There are polyominoes admitting many hexagon tilings :



A $1 \times n$ rectangle tiles the plane as an hexagon in $n-1$ ways and as a square in only 1 way.

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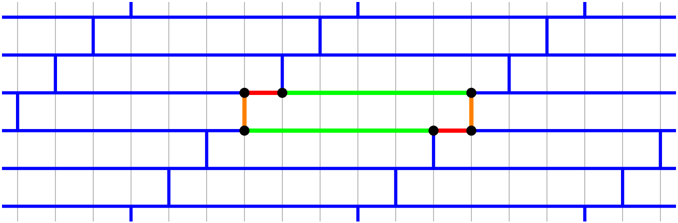

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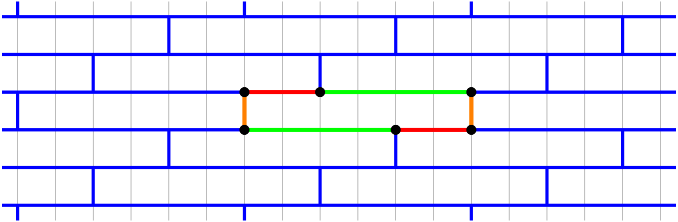

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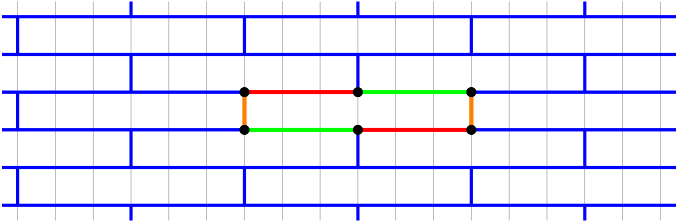

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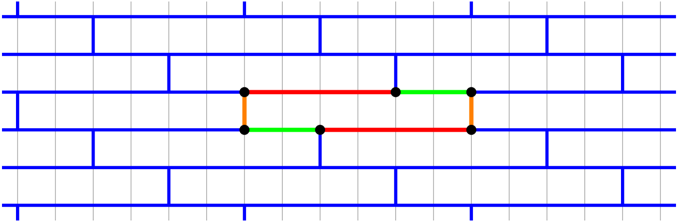

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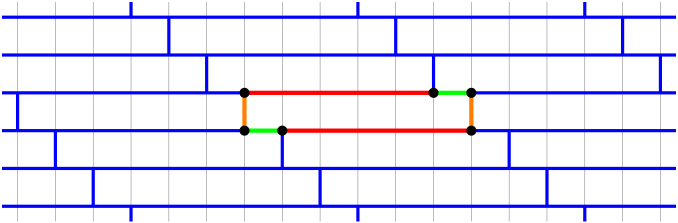

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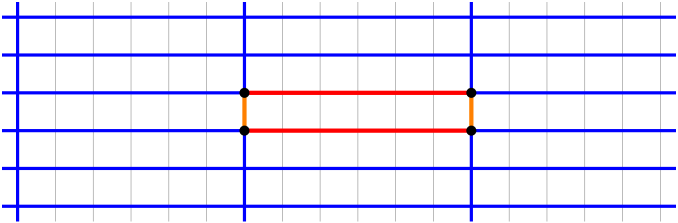

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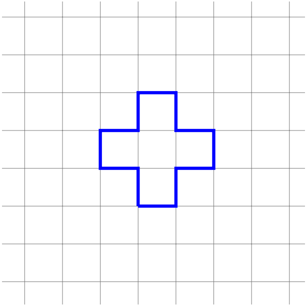
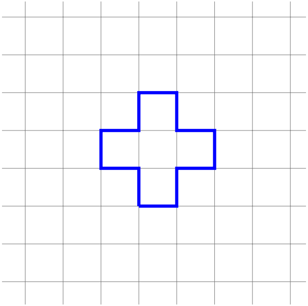
Square Tilings

The pentomino has two distinct square factorizations :





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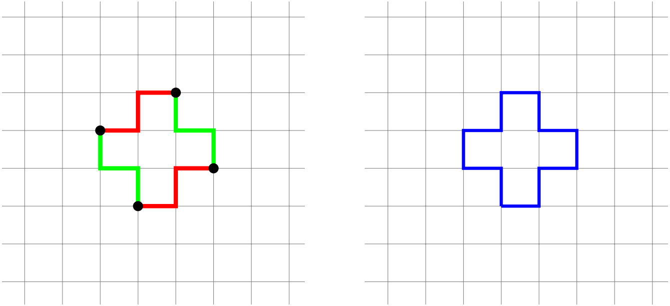

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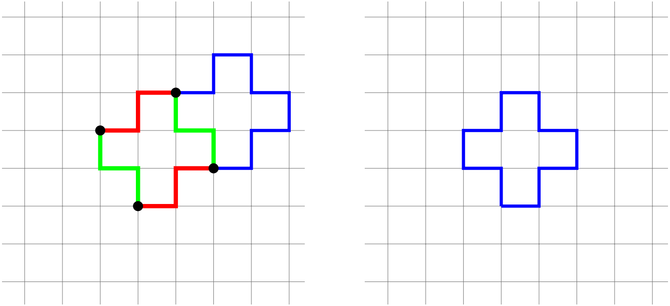

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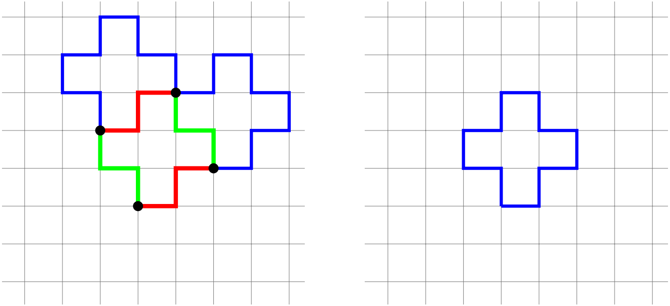

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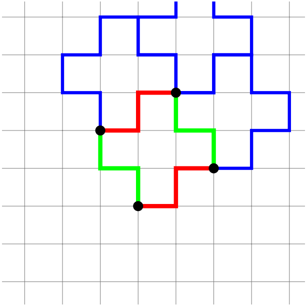

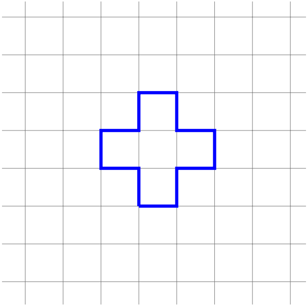

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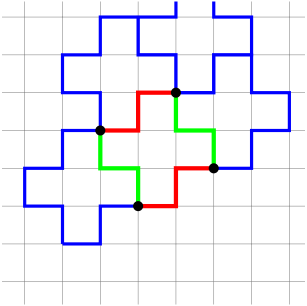

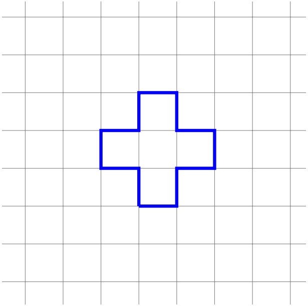

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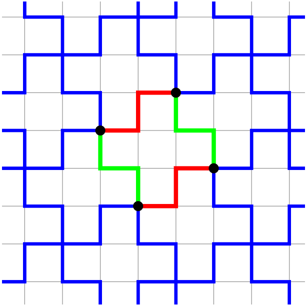

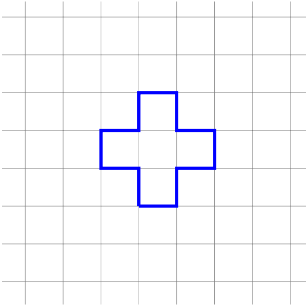

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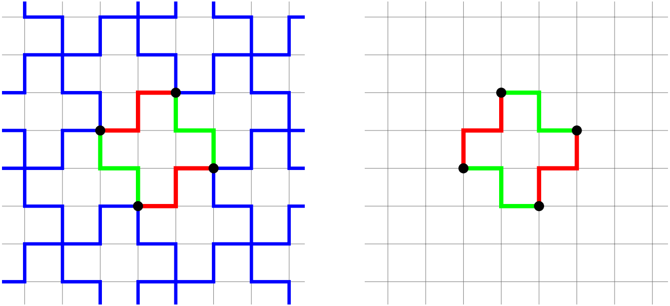

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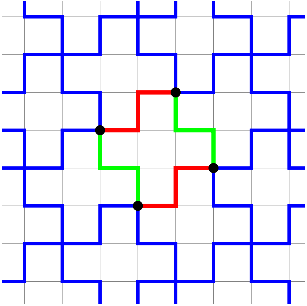

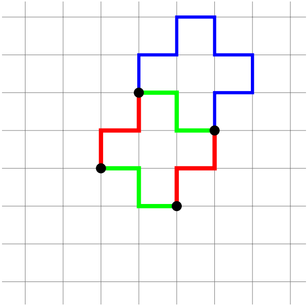

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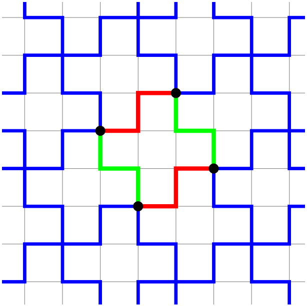

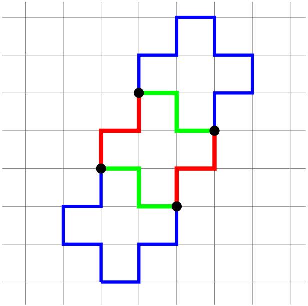

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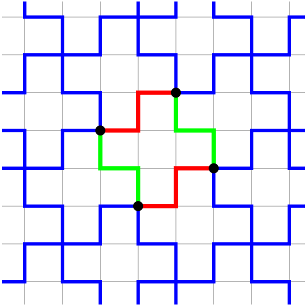

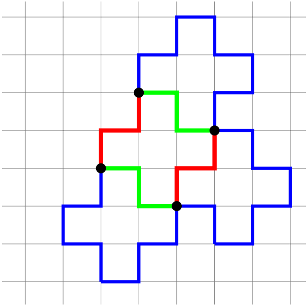

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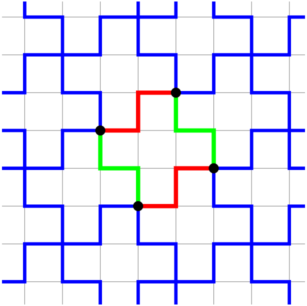

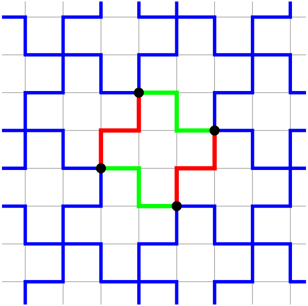

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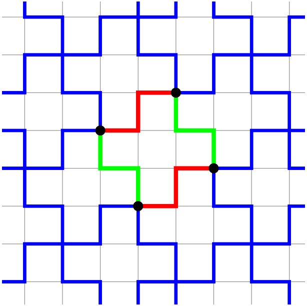
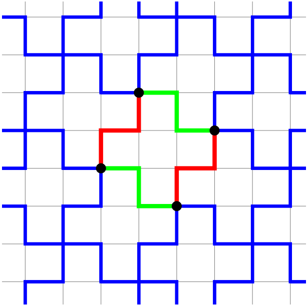




Conjecture (Brlek, Dulucq, Fédou, Provençal 2007)

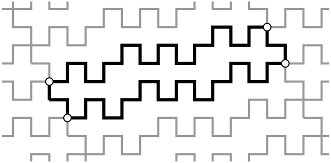
A tile has at most 2 square factorizations.

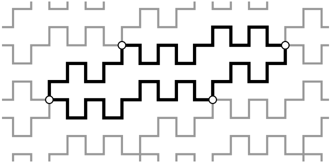
Palindromes in Prime Double Square Tiles

Conjecture (X. Provençal and L. Vuillon, 2008 in the PK-4214)

If $XY\widehat{X}\widehat{Y} \equiv WZ\widehat{W}\widehat{Z}$ are distinct Beauquier-Nivat factorizations of a prime double square tile, then X, Y, W and Z are palindromes.

Note : a palindrome is a word that reads the same forward as it does backward.





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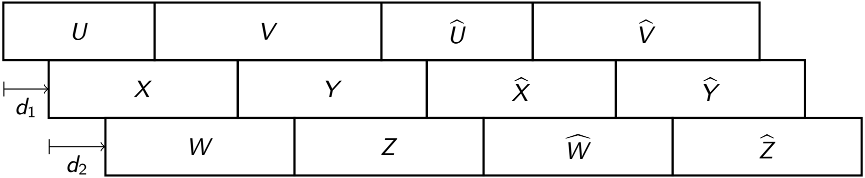
Idea of the proof : at most 2 square factorizations

Lemma (Brlek, Fédou, Provençal, 2008)

The factorizations $UV\widehat{U}\widehat{V} \equiv_{d_1} XY\widehat{X}\widehat{Y}$ *of a double square tile must alternate, that is* $0 < d_1 < |U| < d_1 + |X|$.

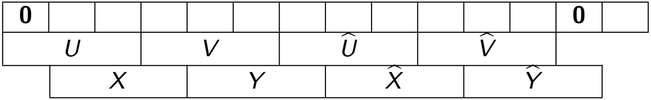
Suppose that there is a triple square tile having the following boundary :

$$UV\widehat{U}\widehat{V} \equiv_{d_1} XY\widehat{X}\widehat{Y} \equiv_{d_2} WZ\widehat{W}\widehat{Z}.$$



Examples

Suppose that $|U| = |V| = |X| = |Y| = |W| = |Z| = 3$.



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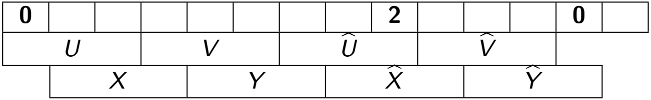

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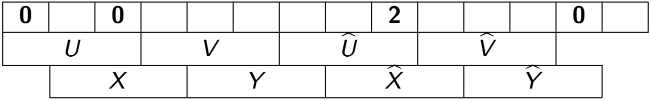

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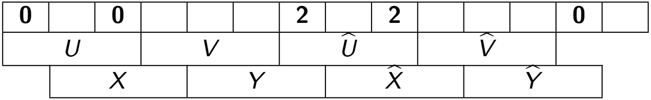

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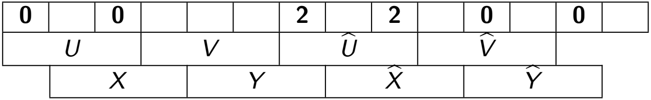

Examples

Suppose that $|U| = |V| = |X| = |Y| = |W| = |Z| = 3$.

0		**0**		**2**		**2**		**2**		**0**		**0**	
U			V			$\widehat{U}$			$\widehat{V}$				
	X			Y			$\widehat{X}$			$\widehat{Y}$			

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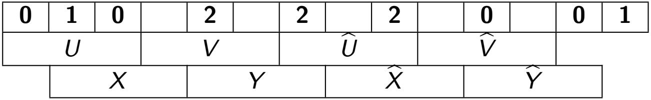

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Although, there are words having more than two square factorizations. An example of length 36 was provided by X. Provençal :

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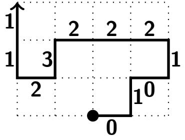
Note that the factor **221003** is a closed path...

First differences sequence

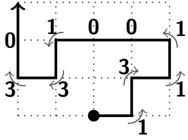
The first differences sequence of $w \in (\mathbb{Z}_4)^*$

$$\Delta w = (w_2 - w_1) \cdot (w_3 - w_2) \cdots (w_n - w_{n-1}).$$

represents the sequence of turns of the path.



$w = \mathbf{01012223211}$



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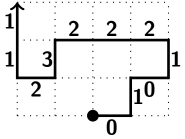

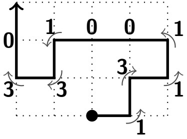

$w = \mathbf{01012223211}$ $\qquad$ $\Delta w = \mathbf{1311001330}$

We also consider $\Delta[w]$ well defined on the conjugacy classes :

$$\Delta[w] = (w_2 - w_1) \cdot (w_3 - w_2) \cdots (w_n - w_{n-1}) \cdot (w_1 - w_n) = \Delta w \cdot (w_1 - w_n).$$

Turning number

The turning number of a path w is $\mathcal{T}(w) = \frac{|\Delta w|_{\mathbf{1}} - |\Delta w|_{\mathbf{3}}}{4}$ and corresponds to its total curvature divided by 2π (Wikipedia). We have that

- $\mathcal{T}(w) = -\mathcal{T}(\widehat{w})$ for all path $w \in \Sigma^*$
- $\mathcal{T}([w]) = \pm 1$ for all simple and closed path w.

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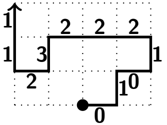
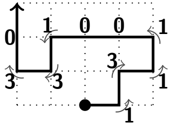
For example,

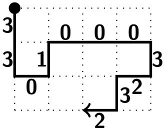


$w = \mathbf{01012223211}$

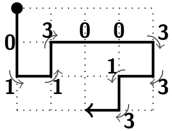


$\Delta w = \mathbf{1311001330}$

$\mathcal{T}(w) = 1/4$



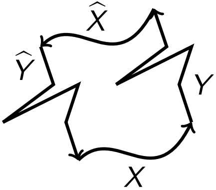
$\widehat{w} = \mathbf{33010003232}$



$\Delta \widehat{w} = \mathbf{0113003313}$

$\mathcal{T}(\widehat{w}) = -1/4$

Turning number



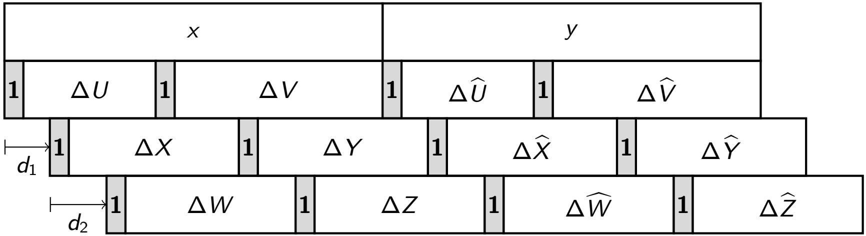
Then, for a square tile, the sum of the four angles between X, Y, $\widehat{X}$ and $\widehat{Y}$ must be 2π.

Lemma (Blondin-Massé, Brlek, Garon, L. 2010)

Si $XY\widehat{X}\widehat{Y}$ est la frontière orientée positivement d'une tuile carrée, alors

$$\Delta[XY\widehat{X}\widehat{Y}] = \Delta X \cdot \mathbf{1} \cdot \Delta Y \cdot \mathbf{1} \cdot \Delta\widehat{X} \cdot \mathbf{1} \cdot \Delta\widehat{Y} \cdot \mathbf{1}.$$

Idée de la preuve : au plus 2 factorisations carrées



On s'intéresse aux moitiés du contour

$$\begin{aligned} x &= x_0 x_1 x_2 \cdots x_{n-1} = \mathbf{1} \cdot \Delta U \cdot \mathbf{1} \cdot \Delta V, \\ y &= y_0 y_1 y_2 \cdots y_{n-1} = \mathbf{1} \cdot \Delta \widehat{U} \cdot \mathbf{1} \cdot \Delta \widehat{V}. \end{aligned}$$

One have $x_i = y_i = \mathbf{1}$ for all $i \in I$ where
$I = \{0, d_1, d_1 + d_2, |U|, d_1 + |X|, d_1 + d_2 + |W|\} \subseteq \mathbb{Z}_n$.

Idée de la preuve : au plus 2 factorisations carrées

On définit trois réflexions sur $\mathbb{Z}_n$:

$$\begin{aligned} s_1 : i &\mapsto |U| - i, \\ s_2 : i &\mapsto |X| + 2d_1 - i, \\ s_3 : i &\mapsto |W| + 2(d_1 + d_2) - i. \end{aligned}$$

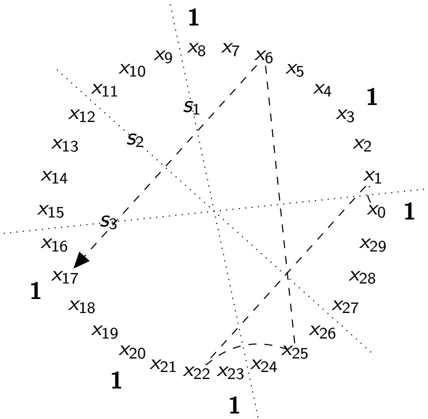
Lemma

Soit $i \in \mathbb{Z}_n$ et $j \in \{1, 2, 3\}$ tels que s_j est admissible sur i. Alors

- $y_i = -x_{s_j(i)}$ *et* $x_i = -y_{s_j(i)}$.
- *Si* $x_i = y_i$, *alors* $x_{s_j(i)} = y_{s_j(i)}$.

Idée de la preuve : au plus 2 factorisations carrées

Soit $n = 30$, $d_1 = 3$, $d_2 = 5$, $|U| = 17$, $|X| = 17$ et $|W| = 15$.
$\mathbf{1} = x_0 = -x_{s_3 s_2 s_1 s_3 s_2(0)} = -x_{17} = -\mathbf{1} = \mathbf{3}$ une contradiction.



On a $s_1 = s_3 s_2 s_1 s_3 s_2$. Si $s_3 s_2 s_1 s_3 s_2$ est un produit admissible de réflexions sur 0, alors $x_0 = -x_{17}$ ce qui est une contradiction. Autrement, des contradictions similaires sont obtenues.

Idée de la preuve : au plus 2 factorisations carrées

Theorem (Blondin Massé, Brlek, Garon, L. 2010)

A tile has at most 2 square factorizations.

Outline

1 Introduction
- Discrete Figures
- Tilings
- Beauquier and Nivat
- Hexagonal and Square Tiles
- A conjecture of Brlek, Dulucq, Fédou and Provençal, 2007
- A conjecture of Provençal and Vuillon, 2008

2 (Idea of the) Proof of the first conjecture

3 (Idea of the) Proof of the second conjecture

4 Open problems

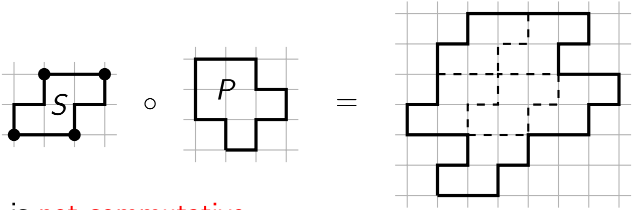
Composition of tiles

The factorization $AB\widehat{A}\widehat{B}$ of a square S allows to define the substitution

$$\varphi_S : \mathbf{0} \mapsto A, \mathbf{1} \mapsto B, \mathbf{2} \mapsto \widehat{A}, \mathbf{3} \mapsto \widehat{B}.$$

For any polyomino P having boundary w we define the composition

$$S \circ P := \varphi_S(w).$$



Note : This is not commutative.

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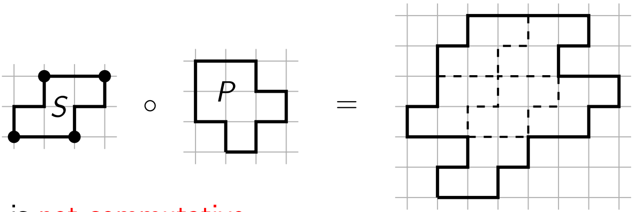

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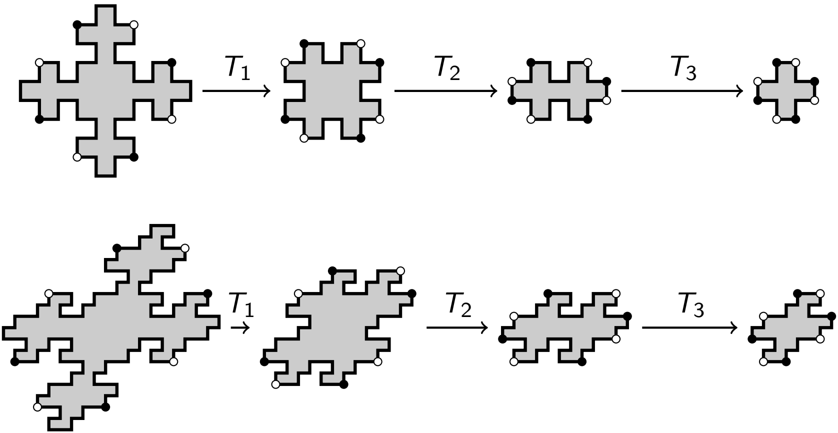
Definition

A polyomino Q is prime if $Q = S \circ P$ implies that S or P is the unit square.

Reduction of double square tiles

Theorem (Blondin Massé, Brlek, Garon, L. (GASCom 2010))

Every double square reduces to a composed cross pentomino.



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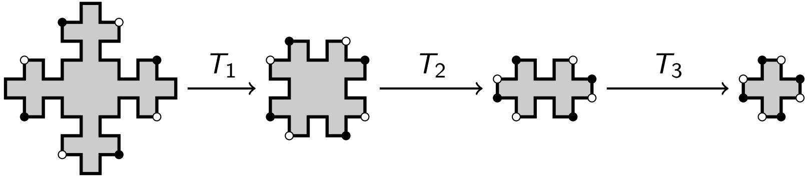


Moreover,

- The transformations T_i are invertible.
- The transformations T_i^{-1} preverve palindromes.

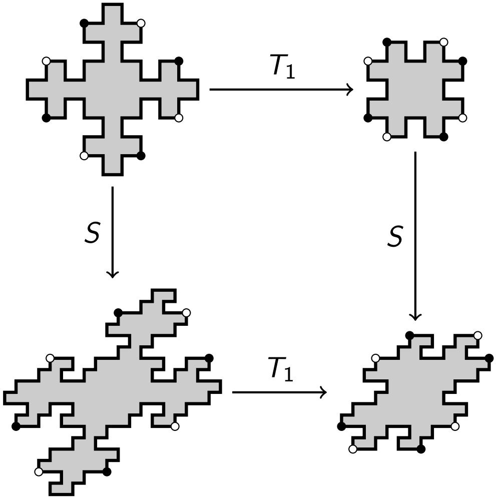
Proposition (Blondin Massé, Brlek, Garon, L. (GASCom 2010))

Let $AB\widehat{A}\widehat{B} \equiv XY\widehat{X}\widehat{Y}$ be the boundary of a double square D. If D reduces to the prime cross pentomino, then A, B, X and Y are palindromes.

Reduction vs Composition

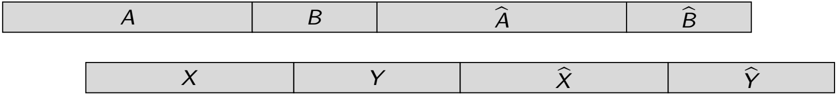
Questions :

- Do every prime double square reduces to the prime cross pentomino ?
- Does the reduction T_i preserve prime tiles ?
- Does the inverse T_i^{-1} preserve composed tiles ?
- Do the following diagram commutes ?



Periods in the boundary of double square tiles

Let $AB\widehat{A}\widehat{B} \equiv XY\widehat{X}\widehat{Y}$ be the factorizations of a double square tile.



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<table>
<tr><td colspan="2">A</td><td colspan="2">B</td><td colspan="2">$\widehat{A}$</td><td colspan="2">$\widehat{B}$</td><td></td></tr>
<tr><td>w_0</td><td>w_1</td><td>w_2</td><td>w_3</td><td>w_4</td><td>w_5</td><td>w_6</td><td>w_7</td><td>w_0</td></tr>
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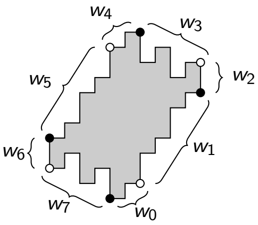
</table>



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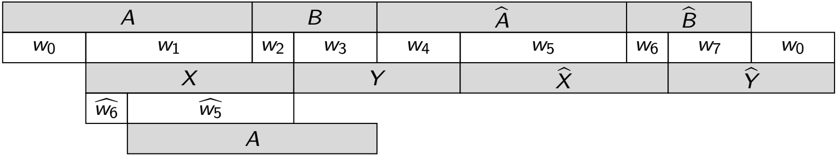

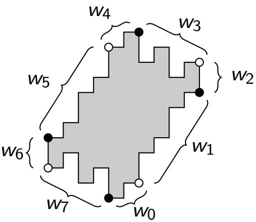

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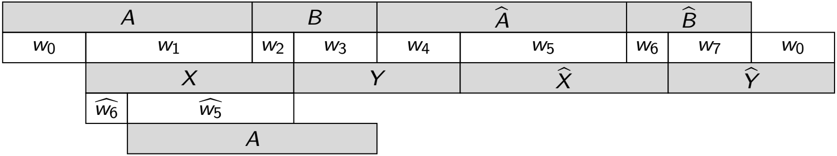
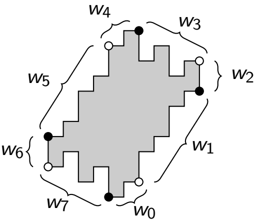


In general

- $|w_{i-1}| + |w_{i+1}|$ is a period of $w_{i-1}w_iw_{i+1}$.

Hence we write

- $w_i = (u_iv_i)^{n_i}u_i$ where $|u_iv_i| = |w_{i-1}| + |w_{i+1}|$.



Transformations

Let $S = (w_0, w_1, w_2, w_3, w_4, w_5, w_6, w_7)$. We define

$\textsc{Shrink}_0(S) = (w_0(v_0 u_0)^{-1}, w_1, w_2, w_3, w_4(v_4 u_4)^{-1}, w_5, w_6, w_7)$,

$\textsc{Swap}_0(S) = (\widehat{w_4}, (v_1 u_1)^{n_1} v_1, \widehat{w_6}, (v_3 u_3)^{n_3} v_3, \widehat{w_0}, (v_5 u_5)^{n_5} v_5, \widehat{w_2}, (v_7 u_7)^{n_7} v_7)$

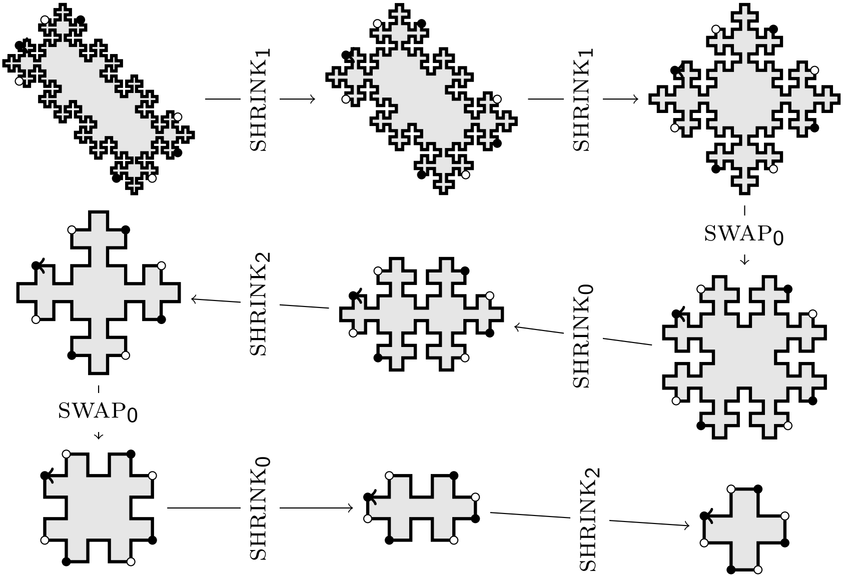
and

$\textsc{Extend}_0(S) = (w_0(v_0 u_0), w_1, w_2, w_3, w_4(v_4 u_4), w_5, w_6, w_7)$

and their conjugates

- $\textsc{Shift}(S) = (w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_0)$,
- $\textsc{Shrink}_i(S) = \textsc{Shift}^{-i} \circ \textsc{Shrink}_0 \circ \textsc{Shift}^{i}(S)$,
- $\textsc{Swap}_i(S) = \textsc{Shift}^{-i} \circ \textsc{Swap}_0 \circ \textsc{Shift}^{i}(S)$,
- $\textsc{Extend}_i(S) = \textsc{Shift}^{-i} \circ \textsc{Extend}_0 \circ \textsc{Shift}^{i}(S)$.

Example of reduction



Idea of the proof

Let $H(w) = |w|_{\mathbf{0}} + |w|_{\mathbf{2}}$ be the number of horizontal steps of the path w and $V(w) = |w|_{\mathbf{1}} + |w|_{\mathbf{3}}$ be its number of vertical steps.

Lemma

Let $S = (w_0, w_1, w_2, w_3, w_4, w_5, w_6, w_7)$ be the factorization of a double square. Then, $H(w_i) = H(w_{i+4})$ and $V(w_i) = V(w_{i+4})$.

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Let $S = (w_0, w_1, w_2, w_3, w_4, w_5, w_6, w_7)$ *be the factorization of a double square. Then,* $H(w_i) = H(w_{i+4})$ *and* $V(w_i) = V(w_{i+4})$.

Lemma

SWAP_i, SHRINK_i *and* EXTEND_i *commute with the composition.*

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Lemma

SWAP_i, SHRINK_i *and* EXTEND_i *commute with the composition.*

Proposition (Blondin-Massé, L., 2010)

Every prime double square reduces to the prime cross pentomino.

Corollary

If $XY\widehat{X}\widehat{Y} \equiv WZ\widehat{W}\widehat{Z}$ are distinct Beauquier-Nivat factorizations of a prime double square tile, then X, Y, W and Z are palindromes.

Outline

1. Introduction
   - Discrete Figures
   - Tilings
   - Beauquier and Nivat
   - Hexagonal and Square Tiles
   - A conjecture of Brlek, Dulucq, Fédou and Provençal, 2007
   - A conjecture of Provençal and Vuillon, 2008
2. (Idea of the) Proof of the first conjecture
3. (Idea of the) Proof of the second conjecture
4. Open problems

Open problems

Some problems are left open :

- Find an algorithm that decides whether a polyomino is prime.
- If $\alpha\alpha$ appears in the boundary word of a double square tile D, where $\alpha \in \{\mathbf{0}, \mathbf{1}, \mathbf{2}, \mathbf{3}\}$, then D is not prime.
- Prove that if $S \circ P$ is a square tile, then so is P.
- Describe the distribution and the proportion of prime square tiles of half-perimeter n as n goes to infinity.
- Show that SHRINK_i and SWAP_i are sufficient to reduce a double square tile : no need to use the more complicated L-SHRINK_i and R-SHRINK_i defined for limit cases.
- Extend the results to 8-connected polyominoes.
- Extend the results to continuous paths and tiles.

Credits

- This research was driven by computer exploration using the open-source mathematical software `Sage`.
- Les images de ce document ont été produites à l'aide de `pgf/tikz`.