Euclidean tilings

Invariant measures

Asymptotic Thurston norm

F. Gautero — Université de Nice - Sophia Antipolis

R. Chazottes — Polytechnique, Paris
J.M. Gambaudo — Université de Nice - Sophia Antipolis

Tilings of $\mathbb{R}^2$

Prototiles: $\mathcal{P} = \{p_1, \cdots, p_n\}$ is a finite set of polygons with colored edges.

Definition

A $\mathcal{P}$-tiling of $\mathbb{R}^2$ is a collection of polygons with colored edges (t_i) (tiles) such that:

1. $\mathbb{R}^2 = \bigcup_i t_i$.
2. *The tiles t_i have disjoint interiors.*
3. *If two tiles t_i, t_j meet, they meet along edges whose colors match.*
4. *Each tile t_i is a translate of some prototile $p_j \in \mathcal{P}$.*

$\Omega_{\mathcal{P}}$ is the set of all $\mathcal{P}$-tilings.

Remark

$\Omega_{\mathcal{P}}$ might be empty: this is an undecidable problem.

The Anderson-Putnam complex $\mathcal{A}_{\mathcal{P}}$

The Anderson-Putnam complex $\mathcal{A}_{\mathcal{P}}$

Definition

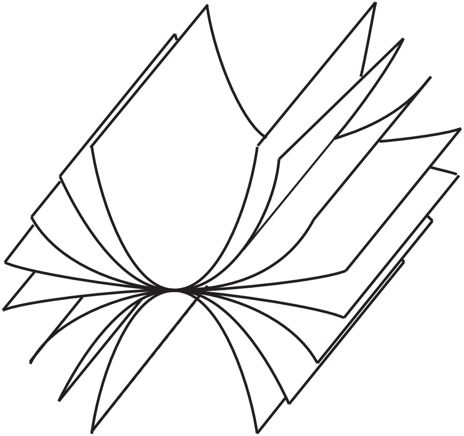
1. *The 2-cells are the prototiles p_j.*
2. *Two 2-cells are glued along the edges e_i, e_j if and only if there is a translation which carries e_i to e_j and the colors match.*

The Anderson-Putnam complex $\mathcal{A}_{\mathcal{P}}$

Definition

1. *The 2-cells are the prototiles p_j.*
2. *Two 2-cells are glued along the edges e_i, e_j if and only if there is a translation which carries e_i to e_j and the colors match. Orient the 2-cells with the orientation of the plane and choose an orientation for the edges.*
3. *Each edge has two sides: the collection of 2-cells where it appears with a $+$ sign in the boundary and the collection of 2-cells where it appears with a $-$ sign.*
   $\Rightarrow$ *Structure of Branched Surface*

The Anderson-Putnam complex $\mathcal{A}_{\mathcal{P}}$



Homology and surfaces

$$H_2(\mathcal{A}_{\mathcal{P}}; \mathbb{R}) = Ker(\partial \colon C_2(\mathcal{A}_{\mathcal{P}}; \mathbb{R}) \to C_1(\mathcal{A}_{\mathcal{P}}; \mathbb{R})).$$

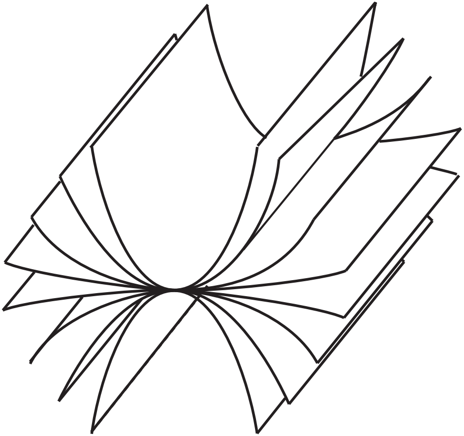
Equivalent to look at the switch equations.

Lemma

Any non-negative integer 2-cycle $c \in H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{Z})$ is represented by a closed (i.e. with no boundary) compact surface S, denoted by $[S] = c$.

This surface S is not necessarily unique up to homeomorphism.

Homology and surfaces



Homology and surfaces

$$H_2(\mathcal{A}_{\mathcal{P}};\mathbb{R}) = Ker(\partial\colon C_2(\mathcal{A}_{\mathcal{P}};\mathbb{R}) \to C_1(\mathcal{A}_{\mathcal{P}};\mathbb{R})).$$

Equivalent to look at the switch equations.

Lemma

Any non-negative integer 2-cycle $c \in H_2^+(\mathcal{A}_{\mathcal{P}};\mathbb{Z})$ is represented by a closed (i.e. with no boundary) compact surface S, denoted by $[S] = c$.

This surface S is not necessarily unique up to homeomorphism.

Thurston semi-norm

$c \in H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{Z})$.
If S is a closed compact surface, $\chi(S)$ is the Euler characteristic of S.

Thurston semi-norm

$c \in H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{Z})$.
If S is a closed compact surface, $\chi(S)$ is the Euler characteristic of S.

Definition

$$||c|| = min_{[S]=c}|\chi(S)|$$

Thurston semi-norm

$c \in H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{Z})$.
If S is a closed compact surface, $\chi(S)$ is the Euler characteristic of S.

Definition

$$||c|| = min_{[S]=c}|\chi(S)|$$

Lemma

1. $||c|| = 0$ *if and only if there is a torus representing* c.
2. $||c_1 + c_2|| \leq ||c_1|| + ||c_2||$.
3. $||nc|| \leq |n|||c||$.

It might happen $||nc|| < |n|||c||$.

Asymptotic Thurston norm

Definition

$$|||c||| = \lim_{n \to +\infty} \frac{||nc||}{n}$$

Well-defined for rational classes.

Asymptotic Thurston norm

Definition

$$|||c||| = \lim_{n \to +\infty} \frac{||nc||}{n}$$

Well-defined for rational classes.

Lemma

The asymptotic Thurston norm is uniformly continuous.

Lemma

1. *The asymptotic Thurston norm is well-defined on* $H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{R})$.
2. $|||c_1 + c_2||| \leq |||c_1||| + |||c_2|||$.
3. $|||nc||| = |n||||c|||$.
4. $|||c||| = 0$ *does not imply that there is a torus representing* c.

A geometric interpretation of the tiling problem

Theorem (Chazottes-Gambaudo-G)

$\Omega_{\mathcal{P}}$ is non-empty (which is equivalent to $\mathcal{P}$ tiles the plane) if and only if the asymptotic Thurston norm vanishes on some non-trivial class $c \in H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{Z})$.

Metrizable topology on $\Omega_{\mathcal{P}}$

$T, T' \in \Omega_{\mathcal{P}}$. $B_\epsilon(0)$: open ball of radius ϵ around the origin.

$$A = \{\epsilon \in (0,1) \text{ s.t. there exists } u \in \mathbb{R}^2 \text{ with } ||u|| < \epsilon \text{ and}$$

$$(T + u) \cap B_{1/\epsilon}(0) = T' \cap B_{1/\epsilon}(0)\}$$

Metrizable topology on $\Omega_{\mathcal{P}}$

$T, T' \in \Omega_{\mathcal{P}}$. $B_\epsilon(0)$: open ball of radius ϵ around the origin.

$$A = \{\epsilon \in (0,1) \text{ s.t. there exists } u \in \mathbb{R}^2 \text{ with } ||u|| < \epsilon \text{ and}$$

$$(T + u) \cap B_{1/\epsilon}(0) = T' \cap B_{1/\epsilon}(0)\}$$

$\delta(T, T') = inf(A)$ if A is non-empty and 1 otherwise.

Lemma

$(\Omega_{\mathcal{P}}, \delta)$ is a compact metric space, together with a continuous action of $\mathbb{R}^2$.

Metrizable topology on $\Omega_{\mathcal{P}}$

$T, T' \in \Omega_{\mathcal{P}}$. $B_\epsilon(0)$: open ball of radius ϵ around the origin.

$$A = \{\epsilon \in (0,1) \text{ s.t. there exists } u \in \mathbb{R}^2 \text{ with } ||u|| < \epsilon \text{ and}$$

$$(T + u) \cap B_{1/\epsilon}(0) = T' \cap B_{1/\epsilon}(0)\}$$

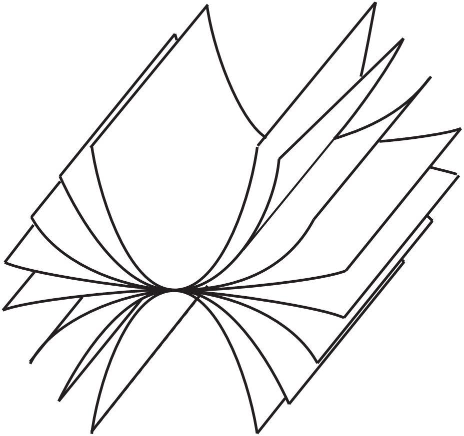
$\delta(T, T') = inf(A)$ if A is non-empty and 1 otherwise.

Lemma

$(\Omega_{\mathcal{P}}, \delta)$ is a compact metric space, together with a continuous action of $\mathbb{R}^2$.

$\mathbb{R}^2$ amenable $\Rightarrow$ Existence of an invariant measure $\Rightarrow$ Existence of a non-negative real 2-cycle in $H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{R})$.

Metrizable topology on $\Omega_{\mathcal{P}}$



Metrizable topology on $\Omega_{\mathcal{P}}$

$T, T' \in \Omega_{\mathcal{P}}$. $B_\epsilon(0)$: open ball of radius ϵ around the origin.

$$A = \{\epsilon \in (0,1) \text{ s.t. there exists } u \in \mathbb{R}^2 \text{ with } ||u|| < \epsilon \text{ and}$$

$$(T+u) \cap B_{1/\epsilon}(0) = T' \cap B_{1/\epsilon}(0)\}$$

$\delta(T, T') = inf(A)$ if A is non-empty and 1 otherwise.

Lemma

$(\Omega_{\mathcal{P}}, \delta)$ is a compact metric space, together with a continuous action of $\mathbb{R}^2$.

$\mathbb{R}^2$ amenable $\Rightarrow$ Existence of an invariant measure $\Rightarrow$ Existence of a non-negative real 2-cycle in $H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{R})$.

Asymptotic Thurston norm and invariant measures

$\mathcal{M}(\Omega_{\mathcal{P}})$ set of invariant measures on $\Omega_{\mathcal{P}}$.

$$\text{Projection } \pi\colon \mathcal{M}(\Omega_{\mathcal{P}}) \to H_2^+(\mathcal{A}_{\mathcal{P}};\mathbb{R})$$

Asymptotic Thurston norm and invariant measures

$\mathcal{M}(\Omega_{\mathcal{P}})$ set of invariant measures on $\Omega_{\mathcal{P}}$.

$$\text{Projection } \pi \colon \mathcal{M}(\Omega_{\mathcal{P}}) \to H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{R})$$

Theorem (Chazottes-Gambaudo-G)

Let $c \in H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{R})$. There exists $\mu \in \mathcal{M}(\Omega_{\mathcal{P}})$ such that $c = \pi(\mu)$ if and only if the asymptotic Thurston norm of c vanishes.

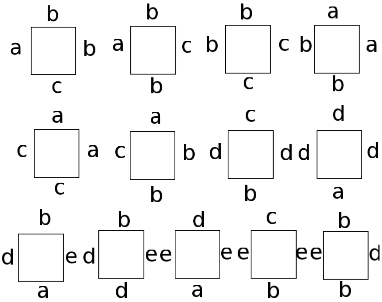
Wang tilings

A Wang tiling is (a tiling made from) a finite collection of unit squares with sides parallel to the axis of $\mathbb{R}^2$ and colored edges.

Theorem (Sadun-Williams)

For any finite collection of polygons $\mathcal{P}$ there is a Wang tiling $\mathcal{W}$ such that $(\Omega_{\mathcal{P}}, \mathbb{R}^2)$ and $(\Omega_{\mathcal{W}}, \mathbb{R}^2)$ are topologically equivalent.

Wang tilings



Wang tilings

A Wang tiling is (a tiling made from) a finite collection of unit squares with sides parallel to the axis of $\mathbb{R}^2$ and colored edges.

Theorem (Sadun-Williams)

For any finite collection of polygons $\mathcal{P}$ there is a Wang tiling $\mathcal{W}$ such that $(\Omega_{\mathcal{P}}, \mathbb{R}^2)$ and $(\Omega_{\mathcal{W}}, \mathbb{R}^2)$ are topologically equivalent.

Proposition

It is sufficient to prove our theorem for Wang tilings.

Hint of proof for Wang tilings

$c = \pi(\mu) \Rightarrow |||c||| = 0$: Forget the colors to obtain a new Wang tiling $\widehat{\mathcal{W}}$ and a new Anderson-Putnam complex $\mathcal{A}_{\widehat{\mathcal{W}}}$. The system $(\Omega_{\mathcal{W}}, \mathbb{R}^2)$ is a sub-system of $(\Omega_{\widehat{\mathcal{W}}}, \mathbb{R}^2)$.

Hint of proof for Wang tilings

$c = \pi(\mu) \Rightarrow |||c||| = 0$: Forget the colors to obtain a new Wang tiling $\widehat{\mathcal{W}}$ and a new Anderson-Putnam complex $\mathcal{A}_{\widehat{\mathcal{W}}}$. The system $(\Omega_{\mathcal{W}}, \mathbb{R}^2)$ is a sub-system of $(\Omega_{\widehat{\mathcal{W}}}, \mathbb{R}^2)$.

Periodic orbits of $\mathbb{R}^2$ (tori) are dense in $(\Omega_{\widehat{\mathcal{W}}}, \mathbb{R}^2)$.
Any invariant measure in $\mathcal{M}(\Omega_{\mathcal{W}})$ is an invariant measure in $\mathcal{M}(\Omega_{\widehat{\mathcal{W}}})$.

Hint of proof for Wang tilings

$c = \pi(\mu) \Rightarrow |||c||| = 0$: Forget the colors to obtain a new Wang tiling $\widehat{\mathcal{W}}$ and a new Anderson-Putnam complex $\mathcal{A}_{\widehat{\mathcal{W}}}$. The system $(\Omega_{\mathcal{W}}, \mathbb{R}^2)$ is a sub-system of $(\Omega_{\widehat{\mathcal{W}}}, \mathbb{R}^2)$.

Periodic orbits of $\mathbb{R}^2$ (tori) are dense in $(\Omega_{\widehat{\mathcal{W}}}, \mathbb{R}^2)$.
Any invariant measure in $\mathcal{M}(\Omega_{\mathcal{W}})$ is an invariant measure in $\mathcal{M}(\Omega_{\widehat{\mathcal{W}}})$.

$c = \pi(\mu)$ in $H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{R})$ is approximated by a sequence of 2-cycles (c_i) in $H_2^+(\mathcal{A}_{\widehat{\mathcal{W}}}; \mathbb{R})$ such that $|||c_i||| = 0$.

Hint of proof for Wang tilings

$c = \pi(\mu) \Rightarrow |||c||| = 0$: Forget the colors to obtain a new Wang tiling $\widehat{\mathcal{W}}$ and a new Anderson-Putnam complex $\mathcal{A}_{\widehat{\mathcal{W}}}$. The system $(\Omega_{\mathcal{W}}, \mathbb{R}^2)$ is a sub-system of $(\Omega_{\widehat{\mathcal{W}}}, \mathbb{R}^2)$.

Periodic orbits of $\mathbb{R}^2$ (tori) are dense in $(\Omega_{\widehat{\mathcal{W}}}, \mathbb{R}^2)$.
Any invariant measure in $\mathcal{M}(\Omega_{\mathcal{W}})$ is an invariant measure in $\mathcal{M}(\Omega_{\widehat{\mathcal{W}}})$.

$c = \pi(\mu)$ in $H_2^+(\mathcal{A}_{\mathcal{P}}; \mathbb{R})$ is approximated by a sequence of 2-cycles (c_i) in $H_2^+(\mathcal{A}_{\widehat{\mathcal{W}}}; \mathbb{R})$ such that $|||c_i||| = 0$.

By continuity $|||c||| = 0$.