

Acyindrical actions on CAT(0) square complexes

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Abstract

For group actions on hyperbolic CAT(0) square complexes, we show that the acylindricity of the action is equivalent to a weaker form of acylindricity phrased purely in terms of stabilisers of points, which has the advantage of being much more tractable for actions on non-locally compact spaces. For group actions on general CAT(0) square complexes, we show that an analogous characterisation holds for the so-called WPD condition. As an application, we study the geometry of generalised Higman groups on at least 5 generators, the first historical examples of finitely presented infinite groups without non-trivial finite quotients. We show that these groups act acylindrically on the CAT(-1) polygonal complex naturally associated to their presentation. As a consequence, such groups satisfy a strong version of the Tits alternative and are residually F_2 -free, that is, every element of the group survives in a quotient that does not contain a non-abelian free subgroup.

Acylindrical actions were first considered by Sela for groups acting on simplicial trees [27]. In Sela's terminology, given a (minimal) action of a group on a simplicial tree, the action is said to be acylindrical if there exists an integer $k \geq 1$ such that no non-trivial element of the group fixes pointwise two points at distance at least k . This definition was extended to actions on arbitrary geodesic metric spaces by Bowditch [4], in his study of the action of the mapping class group of a closed hyperbolic surface on its associated curve complex. Recall that an action of a group G on a metric space X is *acylindrical* if for every $r \geq 0$ there exist constants $L(r), N(r) \geq 0$ such that for every points x, y of X at distance at least $L(r)$, there are at most $N(r)$ elements h of G such that $d(x, hx), d(y, hy) \leq r$. For $r = 0$, one recovers Sela's definition of acylindricity, at least for torsion-free groups. As noticed by Bowditch [4], in the case of group actions on simplicial trees, acylindricity is equivalent to this weaker acylindricity condition at $r = 0$.

Groups that act acylindrically on a hyperbolic spaces share many features with relatively hyperbolic groups, and techniques from dynamics in negative curvature are available to study them. Unfortunately, acylindrical actions on hyperbolic spaces seldom appear naturally in geometric group theory. However, weaker but more frequent forms of acylindricity are sufficient to apply this circle of ideas, as noticed by various authors. In a nutshell, the

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general philosophy is the following: Given a group G acting on a geodesic metric space X , if the space X ‘looks hyperbolic in the direction of some loxodromic element g ’ and if G acts on X ‘acylindrically in the direction of g ’, then most of the machinery carries over to this situation. This was done for instance in [2, 9, 10, 15, 23, 28]. Osin showed the equivalence of all the weak notions of acylindricity involved [24] and proved them to be equivalent to the existence of a non-elementary action of the group on some (generally quite complicated) hyperbolic space. Groups satisfying those properties are now referred to as *acylindrically hyperbolic* groups.

To date, the most general criterion to show the acylindrical hyperbolicity of a group is the following:

Theorem (see [1, Theorem H]). Let G be a group acting by isometries on a geodesic metric space X . Let g be an infinite order element with quasi-isometrically embedded orbits and assume that the following holds:

- g is a *strongly contracting element*, that is, there exists a point x of X such that the closest-point projections on the orbit $\langle g \rangle x$ of the balls of X that are disjoint from $\langle g \rangle x$ have uniformly bounded diameter,
- g satisfies the *WPD condition*, that is, for every $r \geq 0$ there exist constants $m(r), N(r) \geq 0$ such that for every point x of X , there are at most $N(r)$ elements h of G such that $d(x, hx), d(g^{m(r)}x, hg^{m(r)}x) \leq r$.

Then G is either virtually cyclic or acylindrically hyperbolic.

However, checking the acylindricity of an action, or checking that a given hyperbolic element satisfies the WPD condition, is generally tedious. Indeed, while such conditions for actions on simplicial trees boil down to conditions about stabilisers of pairs of points, these conditions involve, for general actions, ‘coarse’ stabilisers of pairs of points, that is, group elements moving a pair of points by a uniformly bounded amount. And while stabilisers of pairs of points lead us to study the set of geodesics between two given points, coarse stabilisers of pairs of points requires a fine understanding of the set of geodesics *between metric balls*. In the case of actions on non-locally compact spaces of dimension at least 2, understanding such sets of geodesics is a highly non-trivial problem.

Let us illustrate these complications with the case of the mapping class group of a closed hyperbolic surface acting on its curve complex. Two vertices of the curve complex at distance at least 3 correspond to curves that fill the surface. Thus, the subgroup fixing two such vertices is finite and, what is more, of uniformly bounded cardinality by a theorem of Hurwitz and the Nielsen Realisation Theorem. In particular, such an action is weakly acylindrical. By contrast, the original proof of the acylindricity of the action by Bowditch required the introduction of the so-called *tight geodesics* of the curve complex and a fine understanding of their combinatorial geometry [4].

When trying to prove the acylindrical hyperbolicity of a group through its action on a given geodesic metric space, a natural approach is to identify classes of group elements, defined in terms of the geometry of the space acted upon and the dynamics of the action at hand, which are good candidates for being strongly contracting and satisfying the WPD condition.

In this article however, we are interested in a slightly different, but related question. We want to find weaker, but more tractable, notions of acylindricity and of the WPD condition that make sense for general actions on geodesic metric spaces, which would nonetheless be equivalent to the usual notions for actions on sufficiently well behaved classes of spaces, paralleling the aforementioned situation for actions on simplicial trees. Here, ‘tractable’ should be interpreted as ‘phrased in terms of stabilisers of points (as in Sela’s original definition) rather than in terms of coarse stabilisers of points’. Let us make this question more precise:

- Question.**
- Is there a weaker form of acylindricity for groups acting on geodesic metric spaces, phrased purely in terms of stabilisers of points, such that, for some nice classes of spaces, such a weaker form of acylindricity is equivalent to the acylindricity of the action?
 - Is there a weaker form of acylindricity for groups acting on geodesic metric spaces, phrased purely in terms of stabilisers of points, such that for such actions on some nice classes of spaces, *every* strongly contracting element g automatically satisfies the WPD condition?
 - Is there a weaker form of the WPD condition for groups acting on geodesic metric spaces, phrased purely in terms of stabilisers of points, such that, for some nice classes of spaces, *every* strongly contracting element g that satisfies such a weak form of the WPD condition also satisfies the WPD condition?

Weak forms of acylindricity have been considered by various authors, for instance Delzant [14] and Hamenstädt [18]. In this article, we will be interested in the following weak form of acylindricity, which is the case $r = 0$ mentioned earlier in the usual definition of acylindricity:

Definition (weak acylindricity). Let G be a group acting on a geodesic metric space X . We say that the action is *weakly acylindrical* if there exist constants $L, N \geq 0$ such that two points of X at distance at least L are pointwise fixed by at most N elements of G .

It should be noted that for groups with a uniform bound on the size of their finite subgroups, weak acylindricity amounts to requiring that two points sufficiently (and uniformly) far apart are fixed by only finitely many elements.

Such a weaker notion of acylindricity is particularly useful when dealing with group actions on polyhedral complexes for which we have a good understanding of the inclusions

of face stabilisers. For instance, an amalgamated product of torsion-free groups of the form $A *_C B$, where B embeds malnormally in A , acts weakly acylindrically on its Bass–Serre tree (this example appeared in [27]). More generally, weak acylindricity is well suited to study groups presented as fundamental groups of complexes of groups, as we will illustrate below.

While acylindricity is a priori much stronger than the weak acylindricity considered here, the main goal of this paper is to show that these notions are in fact equivalent when dealing with actions on particularly well behaved spaces, generalising Bowditch’s observation for actions on simplicial trees. Our first result is the following:

Theorem A. Let G be a group acting weakly acylindrically on a hyperbolic CAT(0) square complex. Then the action is acylindrical.

As an application, we consider *generalised Higman groups*, as introduced by Higman [19]. The generalised Higman groups $H_n, n \geq 4$, were defined by Higman by generators and relations:

$$H_n := \langle a_i, i \in \mathbb{Z}/n\mathbb{Z} \mid a_i a_{i+1} a_i^{-1} = a_{i+1}^2, i \in \mathbb{Z}/n\mathbb{Z} \rangle,$$

These groups are historically the first examples of finitely presented infinite groups without non-trivial finite quotients [19]. In [21], the author studied the action of H_4 on a (non-hyperbolic) CAT(0) square complex naturally associated to its presentation. For $n \geq 5$, H_n acts cocompactly on a CAT(-1) polygonal complex X_n , and in particular on a hyperbolic CAT(0) square complex by taking an appropriate subdivision. Such an action is easily shown to be weakly acylindrical. In particular, we obtain the following result:

Theorem B. For $n \geq 5$, the action of H_n on X_n is acylindrical.

The acylindrical hyperbolicity of generalised Higman groups was first proved by Minasyan–Osin [23], using prior work of Schupp [26]. While acylindrical hyperbolicity alone implies strong consequences for the group (see [24] and details therein), having this well understood acylindrical action of H_n on a hyperbolic complex allows us to obtain results which do not follow solely from the abstract acylindrical hyperbolicity of the group. In particular, we obtain the following:

Corollary C (Strong Tits alternative for generalised Higman groups). For $n \geq 5$, a non-cyclic subgroup of H_n is either contained in a vertex stabiliser, hence embeds in $BS(1, 2)$, or is acylindrically hyperbolic.

Corollary D. For $n \geq 5$, the group H_n is residually F_2 -free, that is, every element of the group survives in a quotient that does not contain a non-abelian free subgroup.

Let us now turn to groups acting on CAT(0) square complexes that are not necessarily hyperbolic. Paralleling what we just did for acylindricity, we will be interested in the following weakening of the WPD condition, which again has the advantage of dealing only with stabilisers of pairs of points:

Definition. Let G be a group acting on a geodesic metric space X and let g be an infinite order element with quasi-isometrically embedded orbits. We say that g satisfies the *weak WPD condition* (or that the action is *weakly acylindrical in the direction of g*) if there exist constants $m, N \geq 0$ such that for every point x of X , there are at most N group elements fixing both x and $g^m x$.

Our second main result is the following:

thm: thmE

Theorem E. Let G be a group acting by isometries on a CAT(0) square complex X . Let g be a strongly contracting element for the CAT(0) metric and suppose that g satisfies the weak WPD condition. Then g satisfies the WPD condition. In particular, G is either virtually cyclic or acylindrically hyperbolic.

As a weakly acylindrical action is weakly acylindrical in the direction of each of its strongly contracting elements, we obtain the following corollary:

Corollary F. Let G be a group acting weakly acylindrically on a CAT(0) square complex X . If g is a strongly contracting element of G for the CAT(0) metric, then g satisfies the WPD condition. In particular, G is either virtually cyclic or acylindrically hyperbolic.

Notice that the Rank Rigidity Theorem for CAT(0) cube complexes of Caprace–Sageev [11, Theorem A] provides us with a way to show the existence of strongly contracting isometries. In particular, we obtain the following corollary:

Corollary G. Let G be a group acting weakly acylindrically on a CAT(0) square complex X such that:

- the action is essential,
- the action does not have a fixed point in $X \cup \partial_\infty X$,
- the complex X is not the product of two unbounded trees.

Then G contains strongly contracting elements for the CAT(0) metric, and every such element satisfies the WPD condition. In particular, G is either virtually cyclic or acylindrically hyperbolic.

For instance, this corollary can be used to recover the acylindrical hyperbolicity of the Higman group on 4 generators directly from the action on its associated (non-hyperbolic) CAT(0) square complex [21]. Indeed, such an action is weakly acylindrical [21, Corollary 3.6], and the Rank Rigidity Theorem of Caprace–Sageev can be applied to show the existence of strongly contracting group elements [21, Remark 2.2].

The Higman group is thus a second natural example, in addition to the mapping class group of a closed hyperbolic surface, of a group acting weakly acylindrically on a polyhedral complex naturally associated to it. As weak acylindricity is a much more tractable condition, and a possibly strictly weaker one, it is natural to ask the following:

Question. Which well-known group actions, which might not be (known to be) acylindrical, are weakly acylindrical?

Moreover, it is natural to ask whether such characterisations of acylindricity and of the WPD condition hold for more general classes of spaces. We thus conclude this introduction with the following:

- Question.**
- For which classes of hyperbolic spaces is the weak acylindricity of an action equivalent to the acylindricity of that action?
 - For which classes of geodesic metric spaces does the weak WPD condition of a strongly contracting isometry implies the WPD condition for that isometry?

Let us explain briefly the organisation of the article. In a nutshell, the strategy we follow is the following: For a given $r > 0$, to every pair of points x, y in X and every group element g moving x and y by at most r , we associate a geodesic quadrangle between the points x, y, gx, gy , and we fill this loop by using an appropriate disc diagram. The aim is then to show that, if x and y are sufficiently far apart, then such ‘filling surfaces’ must have large portions in common. In particular, the associated group elements will necessarily act the same way on a very long common geodesic segment, which is where the weaker forms of acylindricity considered in this paper enter the picture.

Thus, after recalling standard results about the geometry of CAT(0) square complexes and disc diagrams in Section 1, we study in detail the combinatorial geometry of disc diagrams in Section 2. Section 3 studies the way grids (that is, CAT(0) square complexes isometric to Euclidean rectangles tiled by unit squares) can be mapped to a given CAT(0) square complex. With these tools at hand, we prove the main theorems in Section 4. Finally, Section 5 is devoted to the geometry of generalised Higman groups.

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1 Preliminaries on CAT(0) square complexes

This section contains standard results about CAT(0) square complexes which will be used in this article. Throughout this section, X will be a CAT(0) square complex.

1.1 Disc diagrams and the combinatorial Gauß–Bonnet Theorem

A *disc diagram* D over X is a contractible planar square complex endowed with a combinatorial map $D \rightarrow X$ that is an embedding on each square. A disc diagram D over X is

called *reduced* if no two distinct squares of D that share an edge are mapped to the same square of X . We start by an elementary observation.

lem:disc_CAT0

Lemma 1.1. Let $\varphi : D \rightarrow X$ be a reduced disc diagram. Then D is a CAT(0) square complex.

Proof. Since the disc diagram is reduced, the restriction to the link of any vertex is a local isometry. In particular, it sends a simple closed loop of that link to a simple closed loop in the link of the image. As X is a CAT(0) square complex by assumption, simple closed loops in the links of vertices have at least 4 edges. Thus simple closed loops in the links of vertices of D have at least 4 edges, hence D is a CAT(0) square complex. \square

A disc diagram is *non-degenerate* if its boundary is homeomorphic to a circle, and is *degenerate* otherwise. Recall that, by the Lyndon–van Kampen Theorem, one can associate to every non-backtracking loop $S \rightarrow X$ a reduced disc diagram whose restriction to the boundary is the given loop.

Definition 1.2 (disc diagram between geodesics, quadrangle). Let γ_-, γ_+ be two geodesics of X , with vertices u_-, v_- and u_+, v_+ respectively. A *disc diagram between γ_- and γ_+* consists of the following data:

- geodesic paths in γ_u, γ_v in X between u_-, u_+ and v_-, v_+ respectively,
- a reduced disc diagram $\varphi : D \rightarrow X$ whose boundary decomposes as the concatenation of 4 paths P_+, P_v, P_-, P_u such that φ sends P_+, P_v, P_-, P_u bijectively to $\gamma_+, \gamma_v, \gamma_-, \gamma_u$.

The boundary paths P_+, P_- are called the *upper side* and *lower side* of D respectively. The boundary paths P_v, P_u are called the *gates* of D . A non-degenerate disc diagram between two geodesics is called a *quadrangle*.

More generally, given a planar CAT(0) square complex D homeomorphic to a disc and a decomposition of its boundary into geodesic segments P_+, P_v, P_-, P_u as above, we say that D is a square complex *between P_- and P_+* .

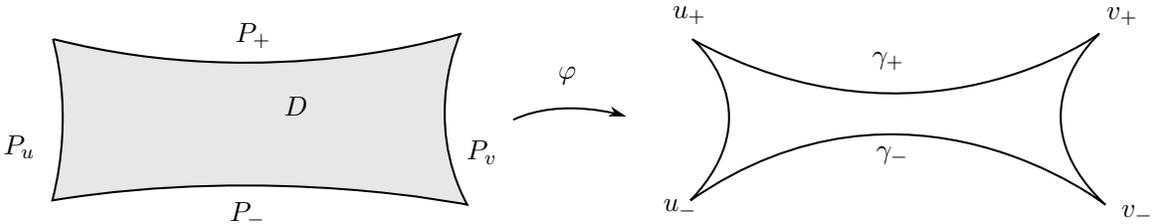


Figure 1: A quadrangle.

fig_quadrangle

We now explain our main tool in controlling the geometry of reduced disc diagrams. Given a planar contractible square complex D , the *curvature* of a vertex v of D is given by:

$$\kappa_D(v) = 2\pi - \pi \cdot \chi(\text{link}(v)) - n_v \frac{\pi}{2},$$

where n_v denotes the number of squares of D containing v . A vertex of D is *internal* if its link is connected and is called a *boundary vertex* otherwise. The curvature of an internal vertex of D is non-positive by Lemma 1.1. The curvature of a boundary vertex is $\frac{\pi}{2}$ if it is contained in a single square of D , and non-positive otherwise. We call a boundary vertex of D a *corner* if it has non-zero curvature. The following version of the combinatorial Gauß–Bonnet Theorem follows the presentation of McCammond–Wise [22, Theorem 4.6].

Theorem 1.3 (Combinatorial Gauß–Bonnet Theorem). *Let D be planar contractible square complex. Then:*

$$\sum_{v \text{ vertex of } D} \kappa_D(v) = 2\pi. \quad \square$$

GaussBonnet

1.2 Hyperplanes in a CAT(0) square complex

We briefly recall some notations and an elementary results about hyperplanes in a CAT(0) square complex. A *hyperplane* is a connected subspace of X which intersects each square of X , isometrically identified with $[-1, 1] \times [-1, 1]$, either in the empty set or in a segment of the form $\{0\} \times [-1, 1]$ or $[-1, 1] \times \{0\}$. An edge of X intersecting a given hyperplane is said to be *dual* to that hyperplane. Reciprocally, one can associate to every edge e of X a unique hyperplane meeting e , and such a hyperplane is said to be *dual* to e . The *combinatorial hyperplane* associated to a given hyperplane (also referred to in the literature as the *carrier* of the hyperplane) is the minimal subcomplex of X containing that hyperplane. Equivalently, it is the reunion of all the faces of X containing an edge dual to that hyperplane. A hyperplane separates X in exactly two connected components. A minimal subcomplex of X containing one of these components is called a *combinatorial half-space*.

In this article, we will only deal with combinatorial hyperplanes, and by a slight abuse of notations, we will denote by H combinatorial hyperplanes and by H_e the combinatorial hyperplane (associated to the hyperplane) dual to a given edge e of X . We recall the following standard result (see for instance [17, Lemma 13.4]):

Lemma 1.4. *Combinatorial hyperplanes and combinatorial half-spaces of a CAT(0) square complex are combinatorially convex. \square*

We also have the following:

Lemma 1.5. *Combinatorial half-spaces are convex for the CAT(0) metric.*

Proof. They are locally convex for the CAT(0) metric, and locally convex connected subsets of a CAT(0) space are globally convex (see for instance [8, Theorem 1.10] for a proof of this fact). \square

The following useful result is well-known, see for instance [17, Lemma 13.1]:

Lemma 1.6. A combinatorial geodesic of a CAT(0) square complex does not contain two distinct edges that define the same hyperplane. \square

If $\varphi : D \rightarrow X$ is a reduced disc diagram, then D is a CAT(0) square complex by Lemma 1.1. The *rails* of a combinatorial hyperplane of D are the two maximal subcomplexes of that combinatorial hyperplane which we do not contain an edge dual to the associated hyperplane.

1.3 Combinatorial intervals

Recall that the *combinatorial interval* between two vertices v, v' of the CAT(0) square complex X , which we denote $\text{Int}_X(v, v')$, is the minimal subcomplex of X containing all the combinatorial geodesics between v and v' . Equivalently, it is the full subcomplex of X associated to the reunion of all the combinatorial geodesics between v and v' . The following is a direct consequence of Lemma 1.6:

Lemma 1.7. The combinatorial interval between two vertices of X is the intersection of all the combinatorial half-spaces containing these two vertices. \square

Thus, Lemma 1.5 implies the following:

Corollary 1.8. Combinatorial intervals are convex for the CAT(0) metric. \square

We also recall the following result (see [7, Theorem 1.16]):

Lemma 1.9. A combinatorial interval of a CAT(0) square complex isometrically embeds in \mathbb{R}^2 with its standard square tiling. \square

2 Disc diagrams and isometric embeddings in the Euclidean plane

As disc diagrams will be our main tool in proving the results presented in the introduction, this section is devoted to study the combinatorial geometry of a reduced disc diagram $\varphi : D \rightarrow X$. The goal of this section is threefold: to obtain a useful criterion ensuring that the CAT(0) square complex D isometrically embeds in \mathbb{R}^2 with its standard square tiling (Proposition 2.3), to obtain a criterion ensuring that the disc diagram $\varphi : D \rightarrow X$ is an isometric embedding (Proposition 2.4), and to prove that for a sufficiently well behaved disc diagram, the map restricts to an isometric embedding on a large subcomplex (Proposition 2.7). Throughout this section again, X will be a given CAT(0) square complex.

2.1 Singularities and (almost) Euclidean quadrangles

Definition 2.1 (singularities, almost Euclidean and Euclidean quadrangles). A *singularity* of a quadrangle $\varphi : D \rightarrow X$ is one of the following:

- an internal vertex of negative curvature,
- a corner of curvature at most $-\pi$,
- a pair of consecutive corners of curvature $-\frac{\pi}{2}$ in the interior of one of the sides P_+ and P_- .

A quadrangle is called *almost Euclidean* if it contains no singularity. It is called *Euclidean* if in addition the boundary of D does not contain two consecutive corners of curvature $-\frac{\pi}{2}$.

More generally, a planar square complex homeomorphic to a disc is *Euclidean* if it contains no internal vertex of negative curvature, no boundary vertex of curvature at most $-\pi$, and no pair of consecutive corners of curvature $-\frac{\pi}{2}$.

The following lemma, which shows that a given quadrangle cannot be ‘too far’ from being almost Euclidean, will be used in Section 4.

Lemma 2.2. Let $\varphi : D \rightarrow X$ be a quadrangle. Then D contains at most 4 singularities.

Proof. Let us denote by $P_i, i = 1, \dots, 4$, the four geodesic sides of the boundary of D . Since each P_i is a combinatorial geodesic, its interior does not contain two consecutive corners of positive curvature (see [21, Lemma 3.8] and its proof). In particular, it follows that

$$\sum_{v \in \overset{\circ}{P}_i} \kappa_D(v) \leq \frac{\pi}{2},$$

and if P_i contains n_i singularities in its interior, a similar argument yields

$$\sum_{v \in \overset{\circ}{P}_i} \kappa_D(v) \leq \frac{\pi}{2} - n_i \frac{\pi}{2}.$$

Since an internal vertex of D has negative curvature if and only if it is a singularity, we have

$$\sum_{v \in \overset{\circ}{D}} \kappa_D(v) \leq -n \frac{\pi}{2},$$

where n is the number of internal singularities of D . Finally, each of the remaining four vertices corresponding to the intersection of two adjacent sides P_i, P_j brings a curvature of at most $\frac{\pi}{2}$. The combinatorial Gauß–Bonnet Theorem thus yields the following inequality:

$$2\pi \leq 4 \cdot \frac{\pi}{2} + 4 \cdot \frac{\pi}{2} - \left(\sum_{1 \leq i \leq 4} n_i \right) \frac{\pi}{2} - n \frac{\pi}{2}$$

and the number $n + \sum_i n_i$ of singularities of D is thus bounded above by 4. \square

2.2 Embeddability in the Euclidean plane

Proposition 2.3. Let D be a Euclidean square complex. Then D embeds isometrically in \mathbb{R}^2 with its standard square tiling.

Proof. Let H be a (combinatorial) hyperplane of D . Let L_+, L_- be the two rails of H . We say that another hyperplane H' *osculates* H if $H \cap H'$ is non-empty but does not contain any square of D .

Claim 1: There exists at most one hyperplane of D that osculates H along L_+ .

In order to prove this claim, first notice that if a square of D meets H , it meets it along an edge, by the curvature condition on Euclidean square complexes. For every hyperplane H' of D osculating H along L_+ , set

$$J_{H'} := H' \cap H.$$

By combinatorial convexity of hyperplanes in a CAT(0) square complex (Lemma 1.4), it follows that each $J_{H'}$ is a sub-segment of L_+ . Moreover, if two such osculating hyperplanes H', H'' define sub-segments of L_+ that meet along a single vertex, then the curvature condition on almost Euclidean complex implies that $H' = H''$. Suppose now by contradiction that there exist at least two hyperplanes of D osculating H along L_+ . It follows from the previous discussion that we can choose a maximal non-empty sub-segment J of L_+ such that no edge of J is contained in a hyperplane of D osculating H along L_+ , and such that the extremities v_1 and v_2 of J are contained in two hyperplanes H_1 and H_2 respectively which osculate H along L_+ . By maximality of J , the curvature condition on almost Euclidean quadrangles implies that each v_i is boundary vertex with curvature $-\frac{\pi}{2}$. By definition of J , there exists no corner of D between v_1 and v_2 , which contradicts the fact that a Euclidean square complex does not contain two consecutive corners of curvature $-\frac{\pi}{2}$. This concludes the proof of Claim 1.

Let H_+ and H_- be the hyperplanes of D osculating H along L_+ and L_- respectively (the argument is similar if there exists only one or zero such osculating hyperplane). Choose isometric embeddings

$$\psi : H \hookrightarrow \mathbb{R}^2, \psi_+ : H_+ \hookrightarrow \mathbb{R}^2 \text{ and } \psi_- : H_- \hookrightarrow \mathbb{R}^2$$

such that the images of ψ, ψ_- and ψ_+ are contained in distinct horizontal hyperplanes of \mathbb{R}^2 and such that

$$\psi(H \cap H_-) = \psi_-(H \cap H_-), \psi(H \cap H_+) = \psi_+(H \cap H_+).$$

From the previous discussion on curvature in almost Euclidean quadrangles, it also follows that

$$\psi(H) \cap \psi_-(H_-) = \psi_-(H \cap H_-), \psi(H) \cap \psi_+(H_+) = \psi_+(H \cap H_+).$$

Thus, we can glue these maps together into a combinatorial embedding

$$H_- \cup H \cup H_+ \hookrightarrow \mathbb{R}^2$$

that is a local isometry, and which sends each of these combinatorial hyperplanes inside a horizontal hyperplane of \mathbb{R}^2 (with its usual square tiling). Reasoning by induction, we have that D is covered by a finite sequence H_i of hyperplanes, which we call *horizontal*, such that, for distinct i and j , we have that $H_i \cap H_j$ is empty if $j \neq i \pm 1$ and is contained in the (unique) rail common to H_i and H_j otherwise. By induction, we thus obtain a combinatorial embedding $\psi : D \hookrightarrow \mathbb{Z}^2$ where each H_i is mapped isometrically into some horizontal hyperplane of \mathbb{Z}^2 .

Claim 2: The map $\psi : D \hookrightarrow \mathbb{Z}^2$ is an isometric embedding.

To prove this claim, let P be a combinatorial geodesic in D , which we can write as a finite concatenation

$$P = P_0 e_1 P_1 e_2 P_2 \dots$$

where each e_i is an edge of D defining one of the horizontal hyperplanes, and P_i is a segment contained in one of the rails of some horizontal hyperplane of D . Thus, $\psi(P)$ consists of the concatenation

$$\psi(P) = \psi(P_0)\psi(e_1)\psi(P_1)\psi(e_2)\psi(P_2)\dots$$

of horizontal segments $\psi(P_i)$ of \mathbb{Z}^2 and vertical edges $\psi(e_i)$. Choosing an orientation for P yields an orientation for each e_i and P_i and hence for their images under ψ . Showing that $\psi(P)$ is an oriented geodesic of \mathbb{Z}^2 thus amounts to showing that all the $\psi(e_i)$ have the same orientation (up or down) and that all the $\psi(P_i)$ have the same orientation (left or right). By contradiction let us assume that this is not the case. Up to an isometry of \mathbb{Z}^2 preserving the set of its horizontal hyperplanes, we thus have two cases to consider:

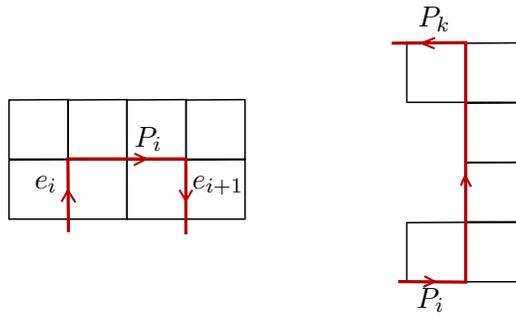


Figure 2: Two impossible configurations.

fig_embedding_Z

Case 1: P contains a sub-segment $e_i P_i e_{i+1}$ such that $\psi(e_i)$ and $\psi(e_{i+1})$ have different orientations (one up, one down, as depicted on the left in Figure 2). But by construction of ψ , this implies that both e_i and e_{i+1} define the same horizontal hyperplane of D , which contradicts Lemma 1.6.

Case 2: P contains a sub-segment of the form $P_i e_{i+1} e_{i+2} \dots e_k P_k$, for some $i < k$, such that $\psi(P_i)$ and $\psi(P_k)$ have different orientations (one left, one right, as depicted on the right in Figure 2). For $i + 1 \leq j \leq k$, if the square of \mathbb{Z}^2 to the left of $\psi(e_j)$ is not contained in $\psi(D)$, then e_j is contained in the boundary of D . If such a square is contained in $\psi(D)$ for every $i + 1 \leq j \leq k$, then the last edge of P_i and the first edge of P_k define the same (hyperplane), contradicting Lemma 1.6. Otherwise, choose a maximal sub-segment of $e_{i+1} \dots e_k$ such that for each edge of it, the square of \mathbb{Z}^2 on its left is not in $\psi(D)$. Then its endpoints are boundary vertices of curvature $-\frac{\pi}{2}$ as D is a non-degenerate disc diagram, and no other corner is between these two corners, contradicting the fact that a Euclidean square complex does not contain two consecutive corners of curvature $-\frac{\pi}{2}$.

This concludes the proof of Claim 2, and thus finishes the proof of Proposition 2.3. \square

2.3 Isometric embeddings

Proposition 2.4. A Euclidean disc diagram $\varphi : D \rightarrow X$ is an isometric embedding.

We will need the following result [17, Lemma 2.11]:

Lemma 2.5. Let $\varphi : X_1 \rightarrow X_2$ be a combinatorial immersion between two CAT(0) square complexes, and assume that the link of a vertex v of X_1 is sent (injectively) to a full subgraph of the link of $\varphi(v)$. Then φ is an isometric embedding. \square

Proof of Lemma 2.4. By Proposition 2.3, we can assume that D is a subcomplex of \mathbb{R}^2 . We now describe an algorithm to *complete* the Euclidean disc diagram $\varphi : D \rightarrow X$ into a Euclidean disc diagram $\varphi' : D' \rightarrow X$, where D' is a subcomplex of \mathbb{R}^2 containing D such that the inclusion $D \hookrightarrow D'$ is an isometric embedding, and such that for every vertex w of D' , the induced map on the link of w sends the link of w in D' to a full subgraph of X .

We proceed by induction and construct maps $\varphi_i : D_i \rightarrow X$ where (D_i) is an increasing sequence of non-degenerate sub-diagram of \mathbb{R}^2 , such no D_i contains two consecutive corners of negative curvature, and such that each inclusion $D_i \hookrightarrow D_{i+1}$ is an isometric embedding. Set $D_0 := D$ and $\varphi_0 := \varphi : D_0 \rightarrow X$. Suppose that D_0, \dots, D_n and $\varphi_0, \dots, \varphi_n$ have been constructed. If D_n contains a vertex w such that the map φ_n sends the link of w to a non-full subgraph of X , then, since the disc diagram is non-degenerate, necessarily w is a corner of curvature $-\frac{\pi}{2}$. Let C be the unique square of \mathbb{R}^2 containing w which is not contained in D_n . Then $C \cap D_n$ consists of exactly two edges, since D_n does not contain two consecutive corners of negative curvature by the inductive hypothesis. Thus, there is

a unique way to extend $\varphi_n : D_n \rightarrow X$ to $\varphi_{n+1} : D_{n+1} \rightarrow X$, where $D_{n+1} := D_n \cup C$. Moreover, the inclusion $D_n \hookrightarrow D_{n+1}$ is an isometric embedding, D_{n+1} does not contain two consecutive corners of negative curvature, and $\varphi_{n+1} : D_{n+1} \rightarrow X$ is reduced.

This algorithm eventually stabilises at some stage $N \geq 0$. Indeed, if we choose a big square of \mathbb{R}^2 containing D , then it contains also every D_i . The map $D \rightarrow X$ thus factorises as $D \hookrightarrow D_N \xrightarrow{\varphi_N} X$. Moreover, as φ_N is reduced by construction, it is automatically an immersion, as D_N is a subcomplex of \mathbb{R}^2 . Thus, φ_N is an isometric embedding by Lemma 2.5, and the same holds for $D \rightarrow X$. \square

2.4 Euclidean quadrangles in disc diagrams

Definition 2.6 (width). A quadrangle $\varphi : D \rightarrow X$ between geodesic segments γ_-, γ_+ of X is *of width at most r* if its sides are at Hausdorff distance at most r in D .

Analogously, a planar CAT(0) square complex D , homeomorphic to a disc, between segments P_- and P_+ is *of width at most r* if P_- and P_+ are at Hausdorff distance at most r in D .

Proposition 2.7. For every $r \geq 0$, there exists a constant $L_{\text{emb}}(r) \geq 0$ such that the following holds: Let $\varphi : D \rightarrow X$ be an almost Euclidean quadrangle, of width at most r , between two geodesics γ_- and γ_+ , and let $\gamma'_- \subset \gamma_-$ be a sub-segment at distance at least $L_{\text{emb}}(r)$ from the endpoints of γ_- . Then there exists a Euclidean sub-quadrangle D' of D , of width at most r , between γ'_- and a sub-segment $\gamma'_+ \subset \gamma_+$.

Proof. Since vertices of almost Euclidean quadrangles have uniformly bounded valence by definition, there exists a constant $N(r)$ such that every combinatorial ball of radius r in a non-degenerate almost Euclidean quadrangle contains at most $N(r)$ edges. Moreover, there exists a constant $L_1(r)$ such that the following holds:

Let $\varphi : D \rightarrow X$ be an almost Euclidean disc diagram of width at most r . Let v_1, v_2 be the vertices of γ_- at distance $2N(r+1) + 1$ from the endpoints u_1, u_2 of γ_- . Since D has width at most r , the combinatorial ball of radius r around v_1 or v_2 disconnects D . In particular, a rail of a hyperplane crossing an edge of γ_- between u_i and v_i which does not cross an edge of $B(v_i, r)$ contains at most $L_1(r)$ edges.

Now set

$$L_{\text{emb}}(r) := (2N(r+1) + 1) + L_1(r).$$

Let $\varphi : D \rightarrow X$ be a non-degenerate almost Euclidean (reduced) disc diagram of width at most r , between two geodesics γ_- and γ_+ , with $|\gamma_-| \geq 2L_{\text{emb}}(r)$. Let v_1, v_2 be the vertices of γ_- at distance $2N(r+1) + 1$ from the endpoints u_1, u_2 of γ_- . By Lemma 1.6, for each $i = 1, 2$, there exists an edge a_i of γ_- between u_i and v_i such that the combinatorial hyperplane H_{a_i} does not meet $B(u_i, r) \cup B(v_i, r)$. In particular, each H_{a_i} crosses γ_+ . Moreover, H_{a_1} and H_{a_2} are disjoint as in addition each $B(v_i, r)$ disconnects D . Thus, H_{a_1} and H_{a_2} defines a Euclidean sub-quadrangle D' of D whose gates are contained in the rails

of some combinatorial hyperplanes (see Figure 3). fig_Euclidean

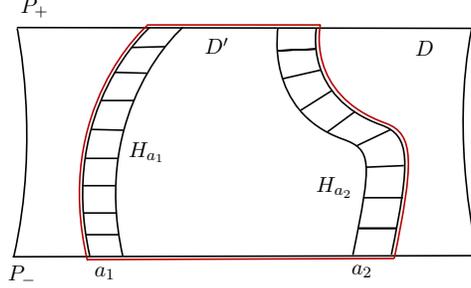


Figure 3: The construction of the Euclidean sub-quadrangle D' .

fig_Euclidean

In particular, $\varphi|_{D'} : D' \rightarrow X$ is a Euclidean quadrangle, and the restriction of φ to D' isometrically embeds in \mathbb{R}^2 by 2.3. Since the rails of each H_{a_i} have length at most $L_1(r)$, and γ_- is at distance at least $L_1(r)$ from a_1 and a_2 , we can choose a sub-quadrangle $\varphi'' : D'' \rightarrow X$ of width at most r between γ'_- and a sub-segment $\gamma''_+ \subset \gamma_+$, which concludes the proof. □

3 Grids and their combinatorial geometry

sec:grids

In this section, we study the way certain subcomplexes of the Euclidean plane with its standard tiling can be mapped to a given CAT(0) square complex. Throughout this section, X is a given CAT(0) square complex.

def:grid

Definition 3.1 (grid). A *grid* of D is a CAT(0) square complex isometric to $I_l \times I_h$, $l \geq 1$, $h \geq 0$, where I_l and I_h denote a simplicial segment on l and h edges respectively. Such a grid is said to be of *length* l and *width* h .

A *grid of X* is a reduced disc diagram $\varphi : D \rightarrow X$.

Remark 3.2. It follows from Lemma 2.5 that a grid of X is an isometric embedding. Therefore, we will sometimes use the term ‘grid of X ’ to denote the image of such a disc diagram.

torisation_grid

Proposition 3.3. Let $\varphi : I_m \times I_n \rightarrow X$ be a combinatorial map such that $\varphi_{I_m \times \{0\}}$ is a combinatorial geodesic. Then φ factorises as

$$I_m \times I_n \xrightarrow{id \times \varphi_n} I_m \times T_n \xhookrightarrow{h} X,$$

where T_n is a simplicial tree, $\varphi_n : I_n \rightarrow T_n$ is a combinatorial map, and $I_m \times T_n \hookrightarrow X$ is an isometric embedding.

Proof. We prove the result by induction on n , for m fixed. The result for $n = 1$ is immediate as combinatorial hyperplanes embed isometrically in a CAT(0) cube complex [25, Theorem 4.10]. Suppose the result is true at rank $n \geq 1$ and consider a map $\varphi : I_m \times I_{n+1} \rightarrow X$ satisfying the assumptions of the lemma. The restriction of φ to $I_m \times I_n$ factorises by the induction hypothesis. Denote by $C_{i,j}$ the square of $I_m \times I_{n+1}$ on the i -th column (starting from the left) and the j -th line (starting from the bottom).

If there exists a $1 \leq i_0 \leq m$ such that $\varphi(C_{i_0,n+1}) = \varphi(C_{i_0,j_0})$, then $\varphi(C_{i,n+1}) = \varphi(C_{i,j_0})$ for every $1 \leq i \leq m$. Indeed, this follows by induction, by starting from C_{i_0,j_0} and moving through adjacent squares in the j_0 -th line, since, in the CAT(0) square complex X , two squares sharing two adjacent edges are the same. Thus, if there exists a $1 \leq i_0 \leq m$ such that $\varphi(C_{i_0,n+1}) = \varphi(C_{i_0,j_0})$, then φ factorises as

$$I_m \times I_{n+1} \xrightarrow{id \times \varphi_{n+1}} I_m \times T_n \hookrightarrow X,$$

where $I_m \times T_n \hookrightarrow X$ comes from the induction hypothesis, $\varphi_{n+1} : I_{n+1} \rightarrow T_n$ is the unique combinatorial map such that $id \times \varphi_{n+1}$ restricts to $id \times \varphi_n$ on $I_m \times I_n$ and is such that $(id \times \varphi_{n+1})(C_{i,n+1}) = (id \times \varphi_n)(C_{i,j_0})$ for every $1 \leq i \leq m$.

If there does not exist a $1 \leq i_0 \leq m$ such that $\varphi(C_{i_0,n+1}) = \varphi(C_{i_0,j_0})$, then write I_{n+1} as the reunion of I_n and an edge e glued along a vertex v , and consider the tree $T_n \cup_{\varphi_n(v)} e'$ obtained by attaching to T_n an edge e' along $\varphi_n(v)$. Then φ factorises as

$$I_m \times I_{n+1} \xrightarrow{id \times \varphi_{n+1}} I_m \times (T_n \cup_{\varphi_n(v)} e') \xrightarrow{h'} X,$$

where $\varphi_{n+1} : I_{n+1} \rightarrow T_n \cup_{\varphi_n(v)} e'$ is the unique combinatorial map that restricts to φ_n on I_n and sends e to e' , and h' restricts to h on $I_m \times T_n$. By construction, the map $I_m \times (T_n \cup_{\varphi_n(v)} e') \xrightarrow{h'} X$ is a local isometry, i.e. it is injective on the link of vertices, as h already is. Moreover, as links of vertices of X have girth at least 4, it follows that for every vertex v of $I_m \times (T_n \cup_{\varphi_n(v)} e')$, the image of the link of v under h' is a full subgraph of the link of $h'(v)$. Thus, h' is an isometric embedding by Lemma 2.5. \square

4 Proof of the main theorems

sec:proofs

This section is devoted to the proof of Theorems A and E. The proofs being extremely similar, we start with the slightly more technical Theorem E and explain in Section 4.5 how to adapt the proof to deduce Theorem A.

4.1 Strongly contracting axes

sec:axes

A CAT(0) square complex has two metrics naturally associated it, depending on whether we are considering the ℓ_1 - or ℓ_2 -metric on its squares. In the ℓ_1 -case, we recover the combinatorial distance on the set of vertices, and in the ℓ_2 -case we recover the CAT(0)

metric. In what follows, we will indicate with subscripts which metric is being considered, whether talking about the translation length $|\cdot|_i$, the distance $d_i(\cdot, \cdot)$, etc.

For the rest of Sections 4.1, 4.3 and 4.4, we assume that we are given a CAT(0) square complex X , a group G acting on it by isometries, and an element $g \in G$ which is strongly contracting (for the ℓ_2 -metric) and satisfies the weak WPD condition. An ℓ_2 -axis of g will mean a geodesic line of X (for the ℓ_2 -metric) on which g acts by translation. An ℓ_1 -axis (or *combinatorial axis*) of g will mean a geodesic line of the 1-skeleton of X (for the ℓ_1 -metric) on which g acts by translation. Combinatorial axes of hyperbolic isometries of CAT(0) square complexes were shown to exist by Haglund [16]. We choose, for $i = 1$ or 2 , an ℓ_i -axis Λ_i for g .

def:tubular

Lemma-Definition 4.1 (tubular constant). Since Λ_2 is strongly contracting by assumption, [3, Corollary 3.4] implies that we can choose a *tubular constant* C_2 such that for every two points x, y of X which project to two points of Λ_2 at distance at least C_2 , then any geodesic from x to y meets the C_2 -neighbourhood of Λ . \square

m:distance_axes

Lemma-Definition 4.2 (the constant δ). There exists a constant $\delta > 0$ such that Λ_1 and Λ_2 are at Hausdorff distance at most δ from one another (for both the ℓ_1 - and the ℓ_2 -metric).

Proof. By [3, Lemma 3.8], there exists a constant C'_2 such that for every pair of points u, v in the C_2 -neighbourhood of Λ_2 , a ball disjoint from the CAT(0) geodesic $[u, v]$ projects on $[u, v]$ to a subset of diameter strictly less than C'_2 . Choose integers $m, m' \geq 1$ such that $m|g|_2 > C_2$ and $m'|g|_2 > C'_2 + |g|_1 + 2$. Let x_1 be a point of Λ_1 and let x_2 be its projection on Λ_2 (and thus $g^{2m+m'}x_2$ is the projection of $g^{n+2m}x_1$ on Λ_2).

Let u be a point of the CAT(0) geodesic between x_1 and $g^{m'+2m}x_1$ which projects to the point $g^m x_2 \in \Lambda_2$. Since $d_2(x_2, g^m x_2) = m|g|_2 > C_2$, there exists a point y in the sub-segment between x and u and a point $y_2 \in \Lambda_2$ in between x_2 and $g^m x_2$ such that $d_2(y, y_2) \leq C_2$. Analogously, let v be a point of the geodesic between x and $g^{m'+2m}x_1$ which projects to the point $g^{m'+m}x_2 \in \Lambda_2$. Since $d_2(g^{m'+m}x_2, g^{m'+2m}x_2) = m'|g|_2 > C_2$, there exists a point z in the sub-segment between v and $g^{m'+2m}x$ and a point $z_2 \in \Lambda_2$ in between $g^{m'+m}x_2$ and $g^{m'+2m}x_2$ such that $d_2(z, z_2) \leq C_2$. By convexity of the CAT(0) metric, it follows that the geodesic between y and z is contained in the C_2 -neighbourhood of Λ_2 .

Let us now consider the combinatorial interval $\text{Int}_X(x_1, g^{m'+2m}x_1)$ between x_1 and $g^{m'+2m}x_1$. By Corollary 1.8 and Lemma 1.9, it is a convex subcomplex (for the CAT(0) metric) and we can think of it as a subcomplex of \mathbb{R}^2 with its standard tiling. Let K be the subset of \mathbb{R}^2 consisting of those points whose orthogonal projection on the bi-infinite line generated by the segment $[y, z]$ is contained in $[y, z]$. It follows from the definition of C'_2 that $\text{Int}_X(x_1, g^{m'+2m}x_1) \cap K$ is contained in the C'_2 -neighbourhood of $[y, z]$. Thus, every combinatorial geodesic from x_1 to $g^{m'+2m}x_1$ contains a sub-interval of ℓ_2 -length at least $d_2(y, z) \geq |g|_1 + 2$, and thus a sub-segment of ℓ_1 -length at least $|g|_1$, which is C'_2 -close to $[y, z]$. In particular, the axis Λ_1 contains a sub-segment of ℓ_1 -length at least $|g|_1$ which is

$(C'_2 + C_2)$ -close to Λ_2 for the ℓ_2 -metric, and thus Λ_1 and Λ_2 are at Hausdorff distance at most $C'_2 + C_2$. \square

An immediate corollary is the following:

def:C_Box

Corollary-Definition 4.3 (the constant C_\square). There exists a constant C_\square such that every grid whose interior is disjoint from the axis Λ_1 projects on Λ_1 (for the ℓ_1 -metric) with a diameter strictly smaller than C_\square . \square

ance_translates

Lemma 4.4. Let γ_1 be a geodesic segment contained in Λ_1 and let h be a group element that moves the endpoints of γ_1 by a distance of at most r (for the ℓ_1 -metric). Let γ'_1 be a sub-segment of γ_1 . Then γ'_1 and $h\gamma'_1$ are at Hausdorff distance at most $2r + 8\delta$ (for the ℓ_1 -metric).

Proof. By lemma [4.2](#), Λ_1 and Λ_2 are at Hausdorff distance at most δ for the ℓ_1 -metric and for the ℓ_2 -metric. Let γ_2, γ'_2 be the ℓ_2 -projections, of γ_1, γ'_1 on the convex subset Λ_2 . The subsets γ_1 and γ_2 (γ'_1 and γ'_2 respectively) are at Hausdorff distance at most δ for the ℓ_2 -metric by construction. We thus have:

$$\begin{aligned} d_1(\gamma'_1, h\gamma'_1) &\leq d_1(\gamma'_1, \gamma'_2) + d_1(\gamma'_2, h\gamma'_2) + d_1(h\gamma'_2, h\gamma'_1), \\ &\leq 4d_2(\gamma'_1, \gamma'_2) + d_1(\gamma'_2, h\gamma'_2), \\ &\leq 4\delta + 2d_2(\gamma'_2, h\gamma'_2) \\ &\leq 4\delta + 2(r + 2\delta) \leq 2r + 8\delta, \end{aligned}$$

the last inequalities following from the convexity of the CAT(0) metric, since h moves the endpoints of γ_1 by at most r . \square

4.2 Staircases

Definition 4.5. A Euclidean CAT(0) square complex $D = D(P_-, P_+)$ between geodesic segments P_- and P_+ is called a *staircase* if P_- contains at least one corner of D in its interior.

lem:staircase

Lemma 4.6. Let $D = D(P_-, P_+)$ be a Euclidean CAT(0) square complex of width at most r between geodesic segments P_- and P_+ of D , and $\varphi_i : D \rightarrow X$ a family of combinatorial maps that all coincide on P_- . Let $k \geq 1$. If P_- contains at least $2r + 2k$ corners, then the φ_i coincide on a sub-geodesic of P_+ of length at least k .

Proof. Recall that D embeds in \mathbb{R}^2 with its standard square tiling by Lemma [1.9](#). Thus, we will assume that D is a subcomplex of \mathbb{R}^2 .

Up to an isometry of \mathbb{R}^2 , we can assume that the following holds: For every horizontal (respectively vertical) edge of P_- , the unique square above it (respectively to its left) is in D (see Figure [4](#)).

Let v and v' be the first and last corners of P_- of curvature $-\frac{\pi}{2}$. We will prove that the φ_i coincide on

$$K := D \cap \text{Int}_{\mathbb{R}^2}(v, v'),$$

where $\text{Int}_{\mathbb{R}^2}(v, v')$ is the combinatorial interval between v and v' . We order the squares of K into a sequence $C_1, C_2 \dots$ by starting from the downmost horizontal hyperplane of K and reading from right to left; Once a horizontal hyperplane has been exhausted, move to the one above it and apply the same procedure.

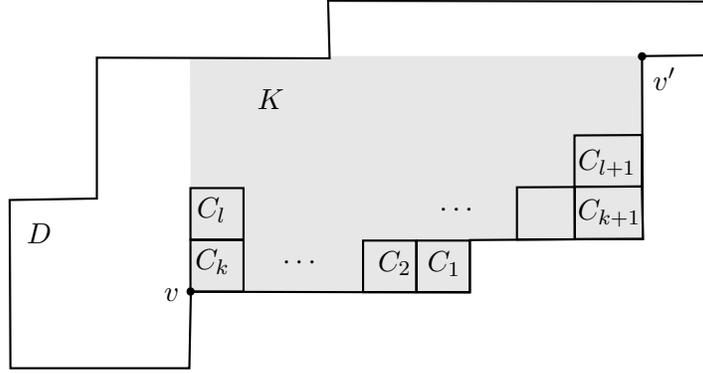


Figure 4: Ordering the squares of K . The subcomplex K is the shaded region.

fig_staircase

We now show by induction that the φ_i coincide on $K_n := \cup_{1 \leq i \leq n} C_i$. This holds for $n = 1$. Indeed, two edges of C_1 are in P_- . As the φ_i coincide on P_- , the CAT(0) condition implies that they also coincide on C_1 . Suppose that the φ_i coincide on K_n for $n \geq 1$. Then the right and bottom edges of C_{n+1} belong to $P_- \cup K_n$, and the same reasoning thus implies that the φ_i coincide on C_{n+1} .

Since P_- contains at least $2r + 2k$ corners, we can choose a vertex w in P_- such that there exist at least $r + k$ corners between w and v , and between w and v' . It thus follows that

$$K \supset D \cap B_{\mathbb{R}^2}(w, r + k),$$

where $B_{\mathbb{R}^2}(\cdot)$ denotes the ball in \mathbb{R}^2 for the combinatorial distance. As the geodesic P_+ meets the r -neighbourhood of w by assumption, it follows that K contains a sub-geodesic of P_+ of length at least k , and the φ_i thus coincide on a sub-geodesic of P_+ of length at least k . \square

4.3 Corridors over the axis Λ_1

Definition 4.7 (Corridor). Let $D = D(\gamma_-, \gamma_+)$ be a Euclidean quadrangle. We say that D is a *corridor* if every vertex in the interior of P_- and P_+ has zero curvature in D .

Remark 4.8. The WPD condition for g is equivalent to requiring that there exist constants L and N such that there do not exist N distinct group elements that fix pointwise two points of Λ_1 at distance at least L . We thus choose two such constants $L, N \geq 0$ for the remaining of this section.

The aim of this section is to prove the following intermediate result:

lem:corridor

Proposition 4.9. For every $r > 0$, there exist constants $L_0(r), N_0(r)$ such that the following holds: For every x, y in Λ_1 , for every sub-segment γ of Λ_1 contained in the sub-segment of Λ_1 between x and y , for every sub-segment $\gamma_- \subset \gamma$ of length at least $L_0(r)$, there exist at most $N_0(r)$ elements h of G such that $d(x, hx), d(y, hy) < r$, and such that there exist a quadrangle between γ and $h\gamma$ together with a sub-quadrangle between γ_- and a sub-segment $\gamma_+ \subset h\gamma$ which is a corridor of width at most $4r + 4C_\square + 16\delta$.

The reason for the constant $4r + 4C_\square + 16\delta$ will become apparent in the next section. A key tool in controlling such quadrangles is the following operations of ‘concatenating’ and ‘piling up’ disc diagrams.

enation_diagram

Definition 4.10 (concatenation of disc diagrams). Let $\varphi : D \rightarrow X$ ($\varphi' : D' \rightarrow X$ respectively) be a quadrangle between two combinatorial geodesic γ_- and γ_+ (γ'_- and γ'_+ respectively). Assume that γ_+ and γ'_- intersect along a non-empty geodesic sub-segment.

The two disc diagrams $\varphi : D \rightarrow X$ and $\varphi' : D' \rightarrow X$ can be *concatenated* into a disc diagram $\Phi : D \cdot D' \rightarrow X$ where $D \cdot D'$ is the planar contractible square complex obtained from the disjoint union of D and D' by identifying a point x in the upper side of D with a point x' in the lower side of D' precisely when $\varphi(x) = \varphi'(x')$.

Definition 4.11 (piling up of disc diagrams). Let γ be a combinatorial geodesic of X . Let (h_i) a sequence of group elements and denote by $\varphi_{h_i} : D(h_i) \rightarrow X$ a quadrangle between γ and $h_i\gamma$. For each integer $i \in \mathbb{Z}$, the map $h_1 \dots h_i \varphi_{h_{i+1}}$ defines a disc diagram between $h_1 \dots h_i\gamma$ and $h_1 \dots h_{i+1}\gamma$. Thus, for each n we can successively concatenate the disc diagrams $h_1 \dots h_i \varphi_{h_{i+1}}$ into a disc diagram between γ and $h_1 \dots h_n\gamma$. We say that this disc diagram is obtained by *piling up* the sequence of disc diagrams $(\varphi_{h_i} : D(h_i) \rightarrow X)_{1 \leq i \leq n}$.

lem:corridor

We now start the proof of Proposition 4.9, which splits in several steps. Throughout this proof, whenever x, y are vertices of Λ_1 , $\gamma \subset \Lambda_1$ is a sub-segment, and $\gamma_- \subset \gamma$ is a sub-segment, we will say that an element g of G satisfies the *property (P_r) with respect to x, y, γ, γ_-* if $d(x, gx), d(y, gy) < r$, and there exists a quadrangle $D(g)$ between γ and $g\gamma$ and a sub-quadrangle $D'(g)$ between γ_- and a sub-segment $\gamma_+ \subset g\gamma$ which is a corridor. The proof is split in several steps.

Step 1. Let x, y be vertices of Λ_1 at distance at least $2(4r + 4C_\square + 16\delta)$, γ a sub-segment of Λ_1 between them, and $\gamma_- \subset \gamma$ a subsegment of length at least $2(4r + 4C_\square + 16\delta)$. Let h be an element of G satisfying the property (P_r) with respect to x, y, γ, γ_- , and denote by

$\varphi_h : D(h) \rightarrow X$ an associated quadrangle and $D'(h)$ the associated sub-quadrangle which is a corridor. Let $k, n \geq 1$ be constants that will be chosen later. Let $\Phi_n : D^n(h) \rightarrow X$ be the disc diagram between γ and $h^n\gamma$ obtained by piling up n copies of the disc diagram $\varphi_h : D(h) \rightarrow X$.

By Lemma 2.3, $D'(g)$ contains a sub-quadrangle which is a grid $G_1(g)$, of length $|\gamma_-| - 2(4r + 4C_\square + 16\delta)$ and width $l \leq 4r + 4C_\square + 16\delta$. We call this integer l the *width* of g . Moreover, by Lemma 4.4, the upper side of $G_1(g)$ and the h -translate of the bottom side of $G_1(g)$ are at Hausdorff distance at most $(4r + 4C_\square + 16\delta) + (2r + 8\delta) = 6r + 4C_\square + 24\delta$. If $|\gamma_-| > 2(4r + 4C_\square + 16\delta) + 2(i-1)(6r + 4C_\square + 24\delta)$ for some $i \geq 1$, then $D'(g)$ contains a sub-quadrangle which is a grid $G_i(g)$, of length $|\gamma_-| - (2(4r + 4C_\square + 16\delta) + 2(i-1)(6r + 4C_\square + 24\delta))$ and width $l \leq 4r + 4C_\square + 16\delta$, over the maximal sub-segment of γ_- at distance at least $4r + 4C_\square + 16\delta + (i-1)(6r + 4C_\square + 24\delta)$ of the extremities of γ_- .

As a consequence, if $|\gamma_-| > k + 2(4r + 4C_\square + 16\delta) + 2(n-1)(6r + 4C_\square + 24\delta)$, then $D^n(g)$ contains a sub-quadrangle $G^n(g)$ between a sub-segment of γ_- and a sub-segment of $g^n\gamma_-$, which is a grid $k \times nl$. Such a grid $G^n(g)$ is obtained as the concatenation of sub-grids $G_{n,i}(g)$, where each $G_{n,i}(g)$ is a sub-grid $k \times l$ of $G_{n-1-i}(g)$ between a sub-segment of γ and a sub-segment of $g\gamma$. We also choose a vertical path $P_n(g)$ of length nl in $G^n(g)$, which we write as the concatenation of n vertical paths $P_{n,i}(g)$ of length l , each $P_{n,i}(g)$ belonging to $G_{n,i}(g)$ (see Figure 5).

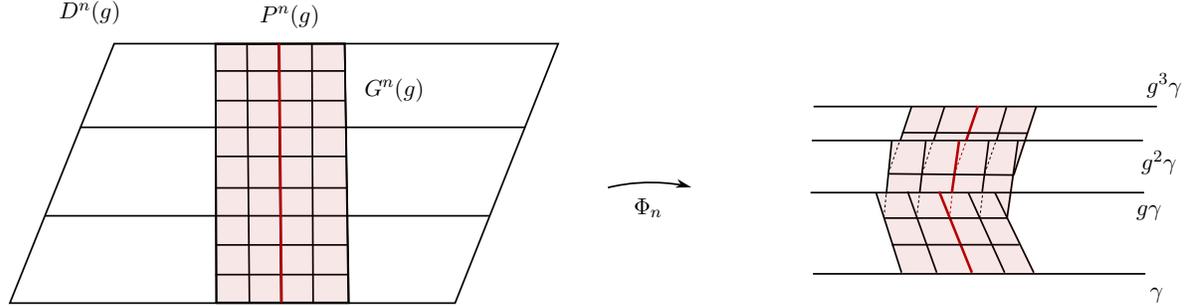


Figure 5: Piling up $n = 3$ copies of a sub-corridor of $D(g)$ of width 3. Here, the (impossible) case where the paths $\Phi_n(P_{n,i}(g))$ and $\Phi_n(P_{n,i+1}(g))$ backtrack on exactly one edge.

fig_pilingup

By Proposition 3.3, the restriction of Φ_n to $G^n(g) \cong I_k \times I_{nl}$ factorises as

$$I_k \times I_{nl} \xrightarrow{id \times \Psi_n} I_k \times T_{nl} \hookrightarrow X,$$

Note that for every $0 \leq i < n$, the paths $\Phi_n(P_{n,i}(g))$ and $\Phi_n(P_{n,i+1}(g))$ backtrack on the same number l' of edges because of Proposition 3.3. If we had $l' < \frac{l}{2}$, then the image $\Phi_n(P_n)$ would contain an isometrically embedded path, and the length of such paths grows linearly with n . In particular for some constant $n_0 \geq 1$ that is independent of x and y , this

length would be bigger than the constant C_\square (Definition ^{def:C_Box}4.3). If k is bigger than C_\square , then it would follow that X would contain an embedded square of side C_\square whose projection on γ has diameter C_\square , contradicting Lemma ^{def:C_Box}4.3.

Step 2. We thus start by defining the following constant:

$$L_0(r) := (\max(L, C_\square, |g|_1) + 36r + 24C_\square + 144\delta) + 2(4r + 4C_\square + 16\delta) + 2(n_0 - 1)(6r + 4C_\square + 24\delta + |g|_1),$$

Let x, y be vertices of Λ_1 at distance at least $L_0(r)$, γ be the sub-segment of Λ_1 between them, and $\gamma_- \subset \gamma$ a subsegment of length at least $L_0(r)$. Let h be a group element that satisfies the property (P_r) with respect to x, y, γ , and γ_- . From the previous paragraph, and using the same notations, it follows that $\Phi_n(P_{n,i}(h))$ and $\Phi_n(P_{n,i+1}(h))$ backtrack on at least $\frac{l}{2}$ edges. For α a real number between 0 and the width of h , we denote by $\ell_\alpha(h)$ the horizontal line of $G_1(h)$ at distance α from P_- , and by $\ell'_\alpha(h)$ the sub-segment $\ell_\alpha(h) \cap G_2(h)$. Since $\Phi_n(P_{n,i}(h))$ and $\Phi_n(P_{n,i+1}(h))$ backtrack on at least $\frac{l}{2}$ edges for each i , it follows that

$$h\varphi(\ell'_{\frac{l}{2}}(h)) \subset \varphi(\ell_{\frac{l}{2}}(h)).$$

Thus, both $h\varphi(\ell'_{\frac{l}{2}}(h))$ and $\varphi(\ell_{\frac{l}{2}}(h))$ are contained in the segment $\varphi(\ell_{\frac{l}{2}}(h))$.

We claim that $h\varphi(\ell'_{\frac{l}{2}}(h))$ and $\varphi(\ell'_{\frac{l}{2}}(h))$ are at Hausdorff distance at most $6r + 4C_\square + 24\delta$. Indeed, this follows from the triangular inequality, as $\varphi(\ell'_{\frac{l}{2}}(h))$ is $(2r + 6C_\square)$ -close to the segment $\varphi(\ell'_0(h))$ by the width assumption, the same holds for $h\ell'_{\frac{l}{2}}(h)$ and $h\ell'_0(h)$, and $\ell'_0(g)$ and $h\ell'_0(g)$ are at most $(2r + 8\delta)$ -close by Lemma ^{lem:distance_t2anslates}4.4.

Thus, $h\varphi(\ell'_{\frac{l}{2}}(h))$ and $\varphi(\ell'_{\frac{l}{2}}(h))$ are contained in the segment $\varphi(\ell_{\frac{l}{2}}(h))$ and are at Hausdorff distance at most $6r + 4C_\square + 24\delta$ from one another. In particular, the two sub-segments share an edge, as they have a length of at least $L + 36r + 24C_\square + 144\delta$.

Step 3. Let us show that, for an element h as in the previous step, the subset $\varphi(\ell'_{\frac{l}{2}}(h))$ is contained in a combinatorial axis of g .

Note that hg has translation length at most $|g|_1 + r$. By concatenating the disc diagrams $(hg)^i \varphi_h : D(h) \rightarrow X$ for $i \geq 0$, the same reasoning as before shows that $hg\varphi_h(\ell'_{l/2}(h))$ and $\varphi_h(\ell'_{l/2}(h))$ are contained in a common segment and are at Hausdorff distance at most $|g|_1 + 6r + 4C_\square + 24\delta$. As we already now that $h\varphi_h(\ell'_{l/2}(h))$ and $\varphi_h(\ell'_{l/2}(h))$ are contained in a segment and are at Hausdorff distance at most $6r + 4C_\square + 24\delta$, it follows that $hg\varphi_h(\ell'_{l/2}(h))$ and $h\varphi_h(\ell'_{l/2}(h))$, and thus $g\varphi_h(\ell'_{l/2}(h))$ and $\varphi_h(\ell'_{l/2}(h))$, are contained in a segment and are at Hausdorff distance at most $|g|_1 + 12r + 8C_\square + 48\delta$. As the length of $\ell'_{l/2}(h)$ is strictly greater than $|g|_1 + 12r + 8C_\square + 48\delta$ by construction, it follows that these two segments share at least an edge. Moreover, they cannot coincide as g is a hyperbolic isometry of X . Thus, the same argument as before shows that $\bigcup_{i \in \mathbb{Z}} g^i \varphi_h(\ell'_{l/2}(h))$ is a combinatorial axis

for g , and it contains $\varphi(\ell'_l(h))$ by construction.

Step 4. Let x, y be vertices of Λ_1 , let γ be the sub-segment of Λ_1 between them, and $\gamma_- \subset \gamma$ a sub-segment of length at least $L_0(r)$. Let us now consider two elements h and h' satisfying (P_r) with respect to x, y, γ and γ_- and having the same width $l \leq 4r + 4C_\square + 16\delta$. Denote by $\varphi_h : D(h) \rightarrow X$ and $\varphi_{h'} : D(h') \rightarrow X$ the associated disc diagrams. Consider elements h_i of G , $i \geq 1$, such that $h_i = h$ if i is odd and $h_i = h'$ otherwise. As before, we can construct the disc diagram $\Phi_n : D^n(h, h') \rightarrow X$ obtained by piling up the disc diagrams $(\varphi_{h_i} : D(h_i) \rightarrow X)_{1 \leq i \leq n}$. As before, $D^n(h, h')$ contains a sub-diagram $G^n(h, h')$ between a sub-segment of γ_- and a sub-segment of $h_1 \cdots h_n \gamma_-$, which is a grid $k \times nl$. Moreover, this map factorises by Proposition 3.3, and we have to consider the image under Φ_n of a vertical path $P_n(h, h')$ of length nl , which is the concatenation of paths $P_{n,i}(h_i) \subset h_1 \cdots h_i D(h_i)$. Here again, note that for every i , the paths $\Phi_n(P_{n,2i-2}(h_{2i-1}))$ and $\Phi_n(P_{n,2i-1}(h_{2i}))$ backtrack on the same number l_{even} of edges, while $\Phi_n(P_{2i-1}(h_{2i}))$ and $\Phi_n(P_{2i}(h_{2i+1}))$ backtrack on the same number l_{odd} of edges. Using the same reasoning, at least one of the two integers l_{even} and l_{odd} is at least $\frac{l}{2}$. Let us assume for instance that this holds for l_{even} . As before, it then follows that $\varphi_h(\ell'_l(h))$ and $(h')^{-1}\varphi_{h'}(\ell'_l(h'))$ are at Hausdorff distance at most $6r + 4C_\square + 24\delta$. But as $(h')^{-1}\varphi_{h'}(\ell'_l(h'))$ and $\varphi_{h'}(\ell'_l(h'))$ are also at Hausdorff distance at most $6r + 4C_\square + 24\delta$ by Step 2, it follows that $\varphi_h(\ell'_l(h))$ and $\varphi_{h'}(\ell'_l(h'))$ are at Hausdorff distance at most $12r + 8C_\square + 48\delta$.

Step 5. We define the following constant:

$$N_0(r) := (4r + 4C_\square + 16\delta + 1)(12r + 8C_\square + 48\delta + 1)N.$$

Let x, y be vertices of Λ_1 , γ the sub-segment of Λ_1 between them, and $\gamma_- \subset \gamma$ a subsegment of length at least $L_0(r)$. Suppose by contradiction that there at least $N_0(r)$ distinct elements satisfying the property (P_r) with respect to x, y, γ and γ_- . For each such element h we consider an associated corridor $\varphi_h : D(h) \rightarrow X$ and use the same notations as above. From Step 4, it follows that for every two such elements h, h' with the same width l , the segments $\varphi_h(\ell'_l(h))$ and $\varphi_{h'}(\ell'_l(h'))$ are at Hausdorff distance at most $12r + 8C_\square + 48\delta$ from one another, and are contained in a segment of X . Choose $(12r + 8C_\square + 48\delta + 1)N$ such elements of the same width. It follows that the intersection ℓ of all the segments $\varphi_h(\ell'_l(h))$ has length at least $L + 12r + 8C_\square + 48\delta = (L + 36r + 24C_\square + 144\delta) - 2(12r + 8C_\square + 48\delta)$. Let ℓ' be the maximal sub-segment of ℓ at distance $6r + 4C_\square + 24\delta$ from the endpoints of ℓ . Each of the $(12r + 24C_\square + 16\delta + 1)N$ elements send ℓ' to a translate contained in ℓ by Step 2. Thus, we can choose at least N distinct such elements whose action on ℓ' coincide. As ℓ' is of length at least L and is contained in a combinatorial axis of g by Step 3, we obtain a contradiction. This finishes the proof of Proposition 4.9.

4.4 Finishing the proof of Theorem E

sec:finish
lem:width

Lemma 4.12. Let γ be a segment of Λ_1 of length at least $2C_\square$, and let h be a group element that moves the endpoints of γ by at most r . Suppose that there exists a reduced disc diagram $\varphi : D \rightarrow X$ between γ and $h\gamma$. Then D has width at most $2r + 4C_\square$.

Proof. Recall that D is a CAT(0) square complex by Lemma 1.1. Let I be the combinatorial interval between the endpoints of the lower path of D , and consider the restriction $\varphi|_I : I \rightarrow X$. If $\varphi|_I : I \rightarrow X$ is non-degenerate, then it is a Euclidean disc diagram, as I isometrically embeds in \mathbb{R}^2 by Lemma 1.9. In such a case, $\varphi|_I$ is an isometric embedding by Lemma 2.4. If $\varphi|_I : I \rightarrow X$ is degenerate, then the restriction of $\varphi|_I$ to each of the maximal subcomplexes of I homeomorphic to a 2-disc is an isometric embedding by the same argument. It follows from Proposition 2.3 and Lemma 4.3 that two combinatorial geodesics of X between the endpoints of γ are at Hausdorff distance at most $2C_\square$ from another. Thus, any two combinatorial geodesics of D between the endpoints of the upper path of D are at Hausdorff distance at most $2C_\square$.

Recall that combinatorial intervals are convex for the CAT(0) metric by Corollary 1.8. Thus, the CAT(0) geodesic P'_+ between the endpoints of the upper path P_+ of D is at Hausdorff distance at most $2C_\square$ from P_+ . Analogously, the CAT(0) geodesic P'_- between the endpoints of the lower path P_- of D is at Hausdorff distance at most $2C_\square$ from P_- . But by convexity of the CAT(0) metric, P'_- and P'_+ are at Hausdorff distance at most r for the ℓ_2 -metric. Thus, P_- and P_+ are at Hausdorff distance at most $2r + 4C_\square$ for the ℓ_1 -metric. \square

Recall that the interval between two vertices of a CAT(0) square complex embeds isometrically in \mathbb{R}^2 endowed with its square tiling (Lemma 1.9). We can thus define the following constant:

Definition 4.13. For every $R \geq 0$, we choose a constant $N_{\text{int}}(R)$ such that there exist at most $N_{\text{int}}(R)$ combinatorial geodesics between two vertices of X at distance at most R .

Further recall that a Euclidean quadrangle $D = D(\gamma_-, \gamma_+)$ isometrically embeds in \mathbb{Z}^2 by Lemma 1.9. We can thus define the following constant:

Definition 4.14. For every $R \geq 0$, we choose a constant $N_{\text{quad}}(R, r)$ on the number of Euclidean quadrangles $D = D(\gamma_-, \gamma_+)$ of width at most $4r + 4C_\square + 16\delta$ and such that $|\gamma_-| \leq R$, up to isometries which preserve pointwise the upper lower sides of the quadrangles.

We are now ready to prove Theorem E. We split the proof in several steps. The first 7 steps deal with points on the axis Λ_1 . Note that, for such points, the acylindricity condition amounts to proving that there exist constants $L_{\text{axis}}(r), N_{\text{axis}}(r)$ such that for every two points x, y of Λ_1 at least $L_{\text{axis}}(r)$ apart, at most $N_{\text{axis}}(r)$ group elements move x and y by at most r .

Let $r > 0$. We start by defining the following constants:

$$\begin{aligned} L_1(r) &:= 2L_{\text{emb}}(4r + 4C_{\square} + 16\delta) + (24r + 8C_{\square} + 78\delta + 2L)(L_0(r) + 2), \\ L_2(r) &:= 5 \cdot L_1(r), \\ N_1(r) &:= (8r + 32\delta + 1)N_{\text{quad}}(L_1(r))N, \\ N_2(r) &:= \max(N_0(r), N_1(r)), \\ N_3(r) &:= (8r + 32\delta + 1)L(r)^2N_{\text{int}}(L(r))N, \\ N_4(r) &:= 5 \cdot 2^{24r+8C_{\square}+78\delta+2L}N_2(r). \end{aligned}$$

Finally, we define the two constants:

$$\begin{aligned} L_{\text{axis}}(r) &:= 3 \cdot L_2(r), \\ N_{\text{axis}}(r) &:= 4\max(N_3(r), N_4(r)). \end{aligned}$$

We now show that, for every vertices x, y of Λ_1 at distance at least $L_{\text{axis}}(r)$, there do not exist $N_{\text{axis}}(r)$ distinct elements h of G such that $d(x, hx), d(y, hy) \leq r$.

By contradiction, suppose that there exist vertices x, y of Λ_1 at distance at least $L_{\text{axis}}(r)$ and $N_{\text{axis}}(r)$ distinct group elements h of G such that $d(x, hx), d(y, hy) \leq r$. For simplicity, we arrange these elements as a finite sequence (h_i) . Choose a taut geodesic γ between x and y .

Step 1. Decompose γ as the concatenation of geodesic segments

$$\gamma := \alpha \cup \gamma_1 \cup \gamma_2 \cup \gamma_3 \cup \beta,$$

such that each of the segments γ_i has length $L_2(r)$. We sort the chosen group elements into four classes, depending on the nature of both $h_i\gamma \cap \gamma_1$ and $h_i\gamma \cap \gamma_3$: empty or non-empty. Since $N(r) = 4\max(N_3(r), N_4(r))$, we can choose at least $\max(N_3(r), N_4(r))$ such elements in the same class.

Assume by contradiction that all the $h_i\gamma \cap \gamma_1$ and $g_i\gamma \cap \gamma_3$ are non-empty. Then since we are considering at least $L(r)^2 \cdot (8r + 32\delta + 1)N_{\text{int}}(L(r))N$ group elements, we can choose at least $(8r + 32\delta + 1)N_{\text{int}}(L(r))N$ such elements such that the $h_i\gamma$ all contain two fixed vertices $v_1 \in \gamma_1$ and $v_3 \in \gamma_3$. Now the sub-segment of $h_i\gamma$ between v_1 and v_3 is in $\text{Int}_X(v_1, v_3)$, which contains at most $N_{\text{int}}(L(r))$ by construction, so we can find at least $(8r + 32\delta + 1)N$ elements such that the $h_i\gamma$ all contain a chosen combinatorial geodesic γ' between v_1 and v_3 . It thus follows that the segments $h_i^{-1}\gamma'$ are contained in γ and are at Hausdorff distance at most $4r + 16\delta$ of one another by Lemma 4.4. Since there are at least $(8r + 32\delta + 1)N$ such elements h_i^{-1} , it thus follows that the action of at least N of them coincide on γ' , and thus N distinct elements of G fix pointwise γ' , which is of length at least $L_2(r) \geq L$, a contradiction.

Step 2. From the previous step, we can thus assume that, for each of the given elements h_i , the segments $h_i\gamma$ and γ_1 , and in particular $h_i\gamma_1$ and γ_1 , are disjoint. Moreover, $h_i\gamma_1$ and γ_1 are at Hausdorff distance at most $2r + 8\delta$ by Lemma 4.4. Thus, we choose for each i a quadrangle $D(h_i)$, of width at most $4r + 4C_\square + 16\delta$ by Lemma 4.12, between γ_1 and $h_i\gamma_1$.

Decompose γ_1 as the concatenation of geodesic segments

$$\gamma_1 := \gamma_{1,1} \cup \dots \cup \gamma_{1,5},$$

such that each of the 5 segments γ_i has length $L_1(r)$. We subdivide each $h_i\gamma_1$ into a concatenation

$$h_i\gamma_1 := \gamma_{1,1}^i \cup \dots \cup \gamma_{1,5}^i,$$

such that one can subdivide the non-degenerate quadrangle $D(h_i)$ into a concatenation of 5 non-degenerate quadrangles:

$$D(h_i) := D_1(h_i) \cdots D_5(h_i),$$

where each $D_k(h_i)$ is a non-degenerate sub-quadrangle between $\gamma_{1,k}$ and $\gamma_{1,k}^i$ which has width at most $4r + 4C_\square + 16\delta$.

Step 3. By Lemma 2.2, for each i at least one of these non-degenerate sub-quadrangles is almost Euclidean. Now, since we have at least $N_{\text{non-deg}}(r) = 5 \cdot 2^{24r+8C_\square+78\delta+2L} N_2(r)$ such elements, there exists an integer $1 \leq k \leq 5$ such that, for at least $2^{24r+8C_\square+78\delta+2L} N_2(r)$ of these group elements, the sub-quadrangle $D_k(h_i)$ is almost Euclidean.

Step 4. Since $\gamma_{1,k}$ is of length

$$L_1(r) = 2L_{\text{emb}}(4r + 4C_\square + 16\delta) + (24r + 8C_\square + 78\delta + 2L)(L_0(r) + 2),$$

we can choose a subsegment $\tilde{\gamma}_{1,k}$ of $\gamma_{1,k}$, of length $(24r + 8C_\square + 78\delta + 2L)(L_0(r) + 2)$ and at distance $L_{\text{emb}}(4r + 4C_\square + 16\delta)$ from the endpoints of $\gamma_{1,k}$. For each i , Proposition 2.7 allows us to choose a sub-segment $\tilde{\gamma}_{1,k}^i$ of $\gamma_{1,k}^i$ and a *Euclidean* sub-quadrangle $\tilde{D}_k(h_i)$ of $D_k(h_i)$ of width at most $4r + 4C_\square + 16\delta$ between $\tilde{\gamma}_{1,k}$ and $\tilde{\gamma}_{1,k}^i$.

Step 5. Now write $\tilde{\gamma}_{1,k}$ as the concatenation of $24r + 8C_\square + 78\delta + 2L$ sub-segments $\tilde{\gamma}_{1,k,l}$ of length $L_0(r) + 2$. For each i and each l , we can choose a sub-segment $\tilde{\gamma}_{1,k,l}^i$ of $\tilde{\gamma}_{1,k}^i$ and a sub-quadrangle $\tilde{D}_{k,l}(h_i)$ of $\tilde{D}_k(h_i)$ of width at most $4r + 4C_\square + 16\delta$ between $\tilde{\gamma}_{1,k,l}$ and $\tilde{\gamma}_{1,k,l}^i$. Among the given $2^{24r+8C_\square+78\delta+2L} N_2(r)N$ group elements, we can now then choose $N_2(r)N$ of them such that for each l , the associated sub-quadrangles $(\tilde{D}_{1,k,l}(h_i))_i$ are all of the same *shape*: corridor or staircase.

Step 6. If for some l , all the $(\tilde{D}_{1,k,l}(h_i))_i$ were corridors, then the fact that $N_2(r) \geq N_0(r)$ would yield a contradiction with Lemma 4.9, so let us assume that they all are staircases. In particular, for each such i , $\tilde{D}_{1,k}(h_i)$ contains at least $24r + 8C_\square + 78\delta + 2L$ corners on $\tilde{\gamma}_{k,1}$. Since we have at least $(4r+2)N_{\text{quad}}(r)N$ group elements, at least $(4r+2)N$ of them define isometric sub-quadrangles. Since $\tilde{D}_{1,k}(h_i)$ has width at most $4r + 12C_\square$ and contains at least

$$24r + 8C_\square + 78\delta + 2L = 2(4r + 4C_\square + 16\delta) + 2(L + 2(4r + 16\delta))$$

corners, it follows from Lemma 4.6 that there exists a geodesic segment P of length $L + 2(4r + 16\delta)$ contained in all the $g_i\gamma$.

Step 7. It now follows that the segments $g_i^{-1}P$ are contained in γ and are at Hausdorff distance at most $4r + 16\delta$ of one another by Lemma 4.4. Since there are at least $(8r + 32\delta + 1)N$ such elements g_i^{-1} , it follows that the action of at least N of them coincide on a geodesic segment of length L , hence N distinct elements of G fix pointwise a sub-segment of length L of Λ_1 , a contradiction.

This concludes the proof that for vertices x, y of the axis Λ_1 at distance at least $L_{\text{axis}}(r)$, at most $N_{\text{axis}}(r)$ elements of G move x and y by a distance of at most r . In the final step, we deal with arbitrary points of X .

Step 8. Recall that the tubular constant C_2 was introduced in Definition 4.1. Let m be an integer such that $m|g|_2 > C_2$. Let n be an integer that will be fixed later, let x be a vertex of X , and let h be a group element such that $d_1(x, hx), d_1(g^{n+2m}x, hg^{n+2m}x) \leq r$. Consider the (unique) CAT(0) geodesic between x and $g^{n+2m}x$. Let also x_2 be the projection of x on Λ_2 (and thus $g^{n+2m}x_2$ is the projection of $g^{n+2m}x$ on Λ_2).

Let u be a point of the geodesic between x and $g^{n+2m}x$ which projects to the point $g^m x_2 \in \Lambda_2$. Since $d_2(x, g^m x) = m|g|_2 > C_2$, there exists a point y in the sub-segment between x and u and a point $y_2 \in \Lambda_2$ in between x_2 and $g^m x_2$ such that $d_2(y, y_2) \leq C_2$. Analogously, let v be a point of the geodesic between x and $g^{n+2m}x$ which projects to the point $g^{m+n} x_2 \in \Lambda_2$. Since $d_2(g^{m+n} x_2, g^{n+2m} x_2) = m|g|_2 > C_2$, there exists a point z in the sub-segment between v and $g^{n+2m}x$ and a point $z_2 \in \Lambda_2$ in between $g^{m+n} x_2$ and $g^{n+2m} x_2$ such that $d_2(z, z_2) \leq C_2$. Since Λ_1 and Λ_2 are at Hausdorff distance at most δ by Definition-Lemma 4.2, choose points y_1, z_1 on Λ_1 which are δ -close from y_2 and z_2 respectively.

Since $d_1(y, hy), d_1(g^{n+2m}z, hg^{n+2m}z) \leq r$ by convexity of the ℓ_2 -metric, it follows that

$$d_1(y_1, hy_1), d_1(z_1, hz_1) \leq 2r + 2\delta + 4C_2.$$

Moreover, we have

$$\begin{aligned} d_2(y_1, z_1) &\geq d_2(x_2, g^{n+2m}x_2) - d_2(x_2, y_2) - d_2(y_2, y_1) - d_2(z_1, z_2) - d_2(z_2, g^{n+2m}x_2) \\ &\geq n|g|_2 - 2\delta, \end{aligned}$$

and thus $d_1(y_1, z_1) \geq n|g|_2 - 2\delta$. Thus, we first choose an integer $n(r)$ (which is independent of the point x) such that $n(r)|g|_2 - 2\delta \geq L_{\text{axis}}(2r + 2\delta + 4C_2)$. Now set:

$$\begin{aligned} m(r) &:= n(r) + 2m, \\ N(r) &:= N_{\text{axis}}(2r + 2\delta + 4C_2). \end{aligned}$$

It thus follows that for every x of X , there exist at most $N(r)$ group elements that move x and $g^{m(r)}x$ by at most r , for otherwise we could find two points of Λ_1 at distance at least $L_{\text{axis}}(2r + 2\delta + 4C_2)$ which are moved by at most $2r + 2\delta + 4C_2$ by $N_{\text{axis}}(2r + 2\delta + 4C_2)$ distinct group elements, a contradiction.

4.5 Deducing Theorem A

sec: ThmA

In this section, we explain how to modify the proof of Theorem E to obtain Theorem A. The proof is almost identical: the proof of Theorem E took place ‘along the axis’ of a strongly contracting WPD element, which displays features of hyperbolic geometry. Under the hypotheses of Theorem A, the whole complex X is hyperbolic, and the following lemmas can be adapted to deal with arbitrary geodesics of X , rather than sub-segments of the combinatorial axis considered in the previous section:

def: tubular Lemma 4.1 still holds in general hyperbolic metric spaces: For *any* geodesic γ of length at least $8\delta'$, δ' the hyperbolicity constant of the space, and any two points x, y of the space that project on γ at distance at least $8\delta'$, then any geodesic from x to y meets the $8\delta'$ -neighbourhood of γ (this follows for instance from the Tree Approximation Theorem for hyperbolic spaces [12, Theorem 8.1]).

lem: distance_axes Lemma 4.2 is reformulated as follows: For every combinatorial geodesic γ of the hyperbolic CAT(0) square complex X , the unique CAT(0) geodesic between the endpoints of γ stays $2C_\square$ -close to γ , where the no-square constant C_\square is reinterpreted as a constant such that X does not contain isometrically embedded $C_\square \times C_\square$ grids.

lem: distance_translates Analogously, Lemma 4.4 is reformulated as follows: Let γ be a geodesic segment and let h be a group element that moves the endpoints of γ by a distance of at most r (for the ℓ_1 -metric). Let γ' be a sub-segment of γ . Then γ' and $h\gamma'$ are at Hausdorff distance at most $2r + 16C_\square$ (for the ℓ_1 -metric).

lem: width Finally, Lemma 4.12 is reformulated as follows: Let γ be a combinatorial geodesic of X of length at least $2C_\square$, and let h be a group element that moves the endpoints of γ by at most r . Suppose that there exists a quadrangle $\varphi : Q \rightarrow X$ between γ and $h\gamma$. Then Q has

width at most $2r + 4C_\square$.

With these modifications, we can prove Theorem A by adapting the proof of Theorem E presented in Sections 4.3 and 4.4.

We first start by proving the analogue of Proposition 4.9, namely: For every $r > 0$, there exist constants $L_0(r), N_0(r)$ such that the following holds: For every combinatorial geodesic γ between two points x, y of X , for every sub-segment $\gamma_- \subset \gamma$ of length at least $L_0(r)$, there exist at most $N_0(r)$ elements h of G such that $d(x, hx), d(y, hy) < r$, and such that there exist a quadrangle between γ and $h\gamma$ and a sub-quadrangle between γ_- and a sub-segment $\gamma_+ \subset h\gamma$ which is a corridor of width at most $4r + 36C_\square = 2(2r + 16C_\square) + 4C_\square$.

The proof, for arbitrary points of X instead of points of Λ_1 , is almost identical to the proof presented in Section 4.3, up to modifying the constants according to the aforementioned changes (in particular, the constant $|g|_1$ is no longer needed in the definition of $L_0(r)$ and $N_0(r)$). The only notable difference is that Step 3 is no longer needed. Indeed, Steps 1-2 and 4-7 yield a geodesic segment of X of length L pointwise fixed by N group elements, which is sufficient to contradict the weak acylindricity of the action (in Section 4.3, Step 3 was there to show that such a geodesic segment is actually contained in a combinatorial axis of the WPD element g , which was necessary to contradict the weak WPD condition).

We then adapt the results of Section 4.4 for arbitrary points of X instead of points of Λ_1 , namely, we prove the following: For every $r > 0$, there exist constants $L(r), N(r)$ such that the following holds: For every two points x, y of X at distance at least $L(r)$, there exist at most $N(r)$ elements h of G such that $d(x, hx), d(y, hy) < r$.

The proof of Steps 1-7 is identical, and yield a geodesic segment of X of length L pointwise fixed by N group elements, which is sufficient to contradict the weak acylindricity of the action (in Section 4.4, Steps 1-7 only dealt with points of the axis Λ_1 and Step 8 dealt with arbitrary points of X).

5 The geometry of generalised Higman groups

sec:Higman

The *generalised Higman groups* H_n , $n \geq 5$ were defined in [19], as the groups with the following presentation:

$$H_n := \langle a_i, i \in \mathbb{Z}/n\mathbb{Z} \mid a_i a_{i+1} a_i^{-1} = a_{i+1}^2, i \in \mathbb{Z}/n\mathbb{Z} \rangle.$$

These groups can naturally be seen as negatively curved polygons of groups (see for instance [6, Theorem 12.28 and Section 12.29]). The local group associated to the polygon is trivial. Order cyclically the edges of the polygon into a sequence (e_i) . The local group associated to each edge e_i of the polygon is a copy of \mathbb{Z} with a chosen generator a_i . The local group associated to each vertex of the polygon is the Baumslag–Solitar group $BS(1, 2)$.

Finally, for each vertex v contained in edges e_i and e_{i+1} , the local maps $G_{e_i} \rightarrow G_v, G_{e_{i+1}} \rightarrow G_v$ send the generators a_i, a_{i+1} respectively to generators b_i, b_{i+1} of $BS(1, 2)$ satisfying the relation $b_i b_{i+1} b_i^{-1} = b_{i+1}^2$.

Thus, $H_n, n \geq 5$ acts cocompactly on a CAT(-1) polygonal complex with strict fundamental domain an n -gon. Stabilisers of faces are trivial, stabilisers of edges are infinite cyclic, and stabilisers of vertices are isomorphic to $BS(1, 2)$. Moreover, for every edge e of X_n with vertices v and v' , one of the morphisms $G_e \hookrightarrow G_v, G_e \hookrightarrow G_{v'}$ is conjugated to $\langle a \rangle \hookrightarrow \langle a, b | aba^{-1} = b^2 \rangle$ while the other one is conjugated to $\langle b \rangle \hookrightarrow \langle a, b | aba^{-1} = b^2 \rangle$.

acylindricity

Lemma 5.1. If v and v' are vertices of X_n at distance at least 3, then the stabilisers of v and v' intersect trivially. In particular, H_n acts weakly acylindrically on X_n for every $n \geq 5$.

Proof. Since H_n acts on the CAT(0) polygonal complex X_n with trivial face stabilisers, fixed point sets of subgroups of H_n are trees in the 1-skeleton of X_n . If an element h of H_n stabilises a sequence e_1, e_2, e_3 of three adjacent edges, then for some vertex v of e_2 , the inclusion $G_e \hookrightarrow G_v$ is conjugated to $\langle a \rangle \hookrightarrow \langle a, b | aba^{-1} = b^2 \rangle$. It then follows that for every edge $e' \neq e$ containing v , the intersection $G_e \cap G_{e'}$ is trivial. Indeed, this is exactly Lemma 2.1 of [21] in the case of 4 generators; the proof being purely about links of vertices, it generalises without any change to $n \geq 5$ generators. Thus, the intersection $G_{e_1} \cap G_{e_2} \cap G_{e_3}$ is trivial. \square

Notice that, for $n \geq 5$, the CAT(-1) polygonal complex X_n can be naturally subdivided into a hyperbolic CAT(0) square complex. Indeed, the subgraph of the one-skeleton of the first barycentric subdivision of X_n , obtained by removing edges corresponding to the inclusion of a vertex of X_n in a polygon of X_n , is naturally the one-skeleton of a CAT(0) square complex. Moreover, such a CAT(0) square complex is quasi-isometric to X_n , and thus hyperbolic. In particular, Theorem A implies the following:

Corollary 5.2. For $n \geq 5$, the action of H_n on X_n is acylindrical. \square

We now give two consequences of the acylindricity of the action, which do not follow automatically from the abstract acylindrical hyperbolicity of the group.

Corollary 5.3 (Strong Tits alternative for generalised Higman groups). For $n \geq 5$, the group H_n satisfies the following form of Tits alternative: A non-cyclic subgroup of H_n is either contained in a vertex stabiliser, hence embeds in $BS(1, 2)$, or is acylindrically hyperbolic. \square

Proposition 5.4. For $n \geq 5$, H_n is residually F_2 -free, i.e. each element of H_n survives in a quotient of H_n which does not contain a non-abelian free subgroup.

Proof. Let h be an element of H_n . We construct by induction a sequence of quotients of H_n

$$H_n \xrightarrow{\pi_1} Q_1 \xrightarrow{\pi_2} Q_2 \rightarrow \dots$$

such that at each stage, Q_k acts acylindrically on a hyperbolic metric space Y_k , and h projects to a non-trivial element of Q_k . Such a construction uses the theory of rotating families of Dahmani–Guirardel–Osin and follows the construction in the proof of [13, Theorem 8.9]; we refer the reader there for additional details. The group $Q_0 := H_n$ acts acylindrically on $Y_0 := X_n$. Let us order all the elements of H_n that act hyperbolically on X_n in a sequence $(h_k)_{k \geq 1}$. Let us assume that the quotients Q_0, Q_1, \dots, Q_k and hyperbolic spaces Y_0, \dots, Y_k are defined. We look at the projection \bar{h}_{k+1} of h_k in Q_k . Since Q_k acts acylindrically on the hyperbolic space Y_k , such an element acts either hyperbolically or elliptically on Y_k by a result of Bowditch [4, Lemma 2.2].

If h_{k+1} projects to a an element of Q_k acting hyperbolically on Y_k , we choose an integer $\alpha_{k+1} \geq 1$ such that

- the coned-off space associated to the action of $\ll \bar{h}_{k+1}^{\alpha_{k+1}} \gg$ on Y_k is hyperbolic,
- the quotient $Q_k / \ll \bar{h}_{k+1}^{\alpha_{k+1}} \gg$ acts acylindrically on the aforementioned coned-off space,
- the projection map $Q_k \rightarrow Q_k / \ll \bar{h}_{k+1}^{\alpha_{k+1}} \gg$ embeds a chosen metric ball of Q_k containing the projection \bar{h} of h .

We then define $Q_{k+1} := Q_k / \ll \bar{h}_{k+1}^{\alpha_{k+1}} \gg$ and Y_{k+1} is the associated coned-off space.

If h_{k+1} projects to a torsion \bar{h}_{k+1} element of Q_k , we set $Q_{k+1} := Q_k$, $Y_{k+1} := Y_k$, and $\alpha_{k+1} \geq 1$ be an integer such that $\bar{h}_{k+1}^{\alpha_{k+1}}$ is trivial.

It thus follows that the quotient

$$Q := H_n / \ll h_k^{\alpha_k}, k \geq 1 \gg$$

of H_n is such that h projects to a non-trivial element.

Let us prove by contradiction that Q does not contain a non-abelian free subgroup. If Q contained such a subgroup, the preimage of such a subgroup under the projection $H_n \rightarrow Q$ would be a free subgroup F of H_n . As elements acting hyperbolically on X_n are mapped to torsion elements of Q by construction, we will derive a contradiction if we can prove that F necessarily contains an element acting hyperbolically.

Claim: The subgroup F contains an element acting hyperbolically on X_n .

If that was not the case, then every element of F acts elliptically on X_n (since X_n has only finitely many isometry types of cells [5]). If the fixed point sets of elements of F pairwise intersect, they globally intersect by a version of the Helly Theorem [20, Proposition 5.3], hence F is contained in a vertex stabiliser, which is absurd as $BS(1, 2)$ does not contain non-abelian free subgroups. Thus, there must exist two elements a, b of F with disjoint fixed point sets. One could adapt the proof of [21, Proposition 3.2] to show that this implies that there exists an element acting hyperbolically on X_n in the subgroup generated by a and b .

In order to remain as self-contained as possible, we give a direct proof that the subgroup $\langle a, b \rangle$ contains an element acting hyperbolically, using the CAT(0) geometry of the space.

By Lemma 5.1, the fixed point sets of a and b are subcomplexes of diameter at most 2. Let x_a, x_b be points of the fixed point sets of $\text{Fix}(a), \text{Fix}(b)$ which realise the distance $\alpha > 0$ between these fixed point sets. Let L be the CAT(0) geodesic between v_a and v_b .

We now show that the angle at x_a (respectively x_b) between L and aL (respectively L and bL) is at least π . Let σ be the (unique) minimal face of X containing the ‘germ of L ’ at x_a , that is, the minimal face of X such that sufficiently small neighbourhoods of x_a in L are contained in σ . If σ is an edge (and thus, x_a is a vertex), then the result follows immediately: Indeed, for every edge e of X and v one of its vertices, an element in the stabiliser of v either fixes e or sends it to an edge making an angle of at least π with e , by definition of the action. So let us assume that σ is a square. If x_a is in the interior of an edge of σ , then L must be perpendicular to that edge since L realises the distance between the fixed point sets, and the result follows immediately. If x_a is a vertex of σ , then no edge of σ is in $\text{Fix}(a)$ since L realises the distance between the two fixed point sets. In particular, for the two edges e, e' of σ containing x_a , the angle at x_a between e and ae (respectively e' and ae') is at least π by the previous remark, whence the angle at x_a between L and aL is at least π .

As the angle at x_a (respectively x_b) between L and aL (respectively L and bL) is at least π , the paths $L \cup aL$ and $L \cup bL$ are geodesics. In particular, the distance between $\text{Fix}(a)$ and $ba\text{Fix}(a)$ is at least $2\alpha - 2$. Reasoning analogously, one shows that, for every $k \geq 2$, the distance between $\text{Fix}(a)$ and $(ba)^k\text{Fix}(a)$ is at least $k\alpha - 2$. In particular, ba does not have bounded orbits, so it does not act elliptically, a contradiction. This proves the claim, and finishes the proof. \square

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