Rigidity of Teichmüller space

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We prove that every quasi-isometry of Teichmüller space equipped with the Teichmüller metric is a bounded distance from an isometry of Teichmüller space. That is, Teichmüller space is quasi-isometrically rigid.

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1 Introduction and statement of the theorem

In this paper we continue our study of the coarse geometry of Teichmüller space begun in Eskin, Masur and Rafi [11]. Our goal, as part of Gromov’s broad program to understand spaces and groups by their coarse or quasi-isometric geometry, is to carry this out in the context of Teichmüller space equipped with the Teichmüller metric. To state the main theorem, let $S$ be a connected surface of finite hyperbolic type. Define the complexity of $S$ to be

$$\xi(S) = 3g(S) + p(S) - 3,$$

where $g(S)$ is the genus of $S$ and $p(S)$ is the number of punctures. Let $T(S)$ denote the Teichmüller space of $S$ equipped with the Teichmüller metric $d_{T(S)}$.

**Theorem 1.1** Assume $\xi(S) \geq 2$. Then, for every $K_S, C_S > 0$ there is a constant $D_S > 0$ such that if

$$f_S : T(S) \to T(S)$$

is a $(K_S, C_S)$–quasi-isometry then there is an isometry

$$\Psi_S : T(S) \to T(S)$$

such that, for $x \in T(S)$,

$$d_{T(S)}(f(x), \Psi(x)) \leq D_S.$$
Recall that a map \( f : \mathcal{X} \to \mathcal{Y} \) from a metric space \((\mathcal{X}, d_{\mathcal{X}})\) to a metric space \((\mathcal{Y}, d_{\mathcal{Y}})\) is a \((K, C)\)-quasi-isometry if it is \(C\)-coarsely onto and, for \(x_1, x_2 \in \mathcal{X}\),

\[
\frac{1}{K} d_{\mathcal{X}}(x_1, x_2) - C \leq d_{\mathcal{Y}}(f(x_1), f(x_2)) \leq K d_{\mathcal{X}}(x_1, x_2) + C.
\]

If equation (1) holds and the map is not assumed to be onto, then \(f\) is called a quasi-isometric embedding. One defines, for a metric space \((\mathcal{X}, d_{\mathcal{X}})\), the group \(\text{QI}(\mathcal{X})\) as the equivalence classes of quasi-isometries from \(\mathcal{X}\) to itself, with two quasi-isometries being equivalent if they are a bounded distance apart. When the natural homomorphism \(\text{Isom}(\mathcal{X}) \to \text{QI}(\mathcal{X})\) is an isomorphism, we say \(\mathcal{X}\) is quasi-isometrically rigid. Then Theorem 1.1 restated is that \(\mathcal{T}(S)\) is quasi-isometrically rigid.

Note also that, by Royden’s theorem [24], \(\text{Isom}(\mathcal{T}(S))\) is essentially the mapping class group (the exceptional cases are the twice-punctured torus and the closed surface of genus 2 where the two groups differ by a finite index). Hence, except for the lower complexity cases, \(\text{QI}(\mathcal{T}(S))\) is isomorphic to the mapping class group. This theorem has also been proven by Brian Bowditch [3] by a different method.

**History and related results**

There is a fairly long history that involves the study of the group \(\text{QI}(\mathcal{X})\) in different contexts. Among these, symmetric spaces are the closest to our setting.

In the case when \(\mathcal{X}\) is \(\mathbb{R}^n\), \(\mathbb{H}^n\) or \(\mathbb{C} \mathbb{H}^n\), the quasi-isometry group is complicated and much larger than the isometry group. In fact, if a self map of \(\mathbb{H}^n\) is a bounded distance from an isometry then it induces a conformal map on \(S^{n-1}\). But every quasiconformal homeomorphism from \(S^{n-1} \to S^{n-1}\) extends to a quasi-isometry of \(\mathbb{H}^n\). This, in particular, shows why the condition \(\xi(S) \geq 2\) in Theorem 1.1 is necessary. When \(\xi(S) = 1\), the Teichmüller space \(\mathcal{T}(S)\) is isometric (up to a factor of 2) to the hyperbolic plane \(\mathbb{H}\) and, as mentioned above, \(\mathbb{H}\) is not rigid.

Pansu [19] proved that other rank 1 symmetric spaces of noncompact type such as quaternionic hyperbolic space \(\mathbb{H} \mathbb{H}^n\) and the Cayley plane \(\mathbb{P}^2(\mathbb{O})\) are rigid. In contrast, higher-rank irreducible symmetric spaces are rigid. This was proven by Kleiner and Leeb [16]; see also Eskin and Farb [7] for a different proof. In our setting, when \(\xi(S) \geq 2\), the space \(\mathcal{T}(S)\) is analogous to a higher-rank symmetric space; see Eskin, Masur and Rafi [11] and Bowditch [3] for discussion about flats in \(\mathcal{T}(S)\). The curve complex \(C(S)\), which plays a prominent role in Teichmüller theory, is analogous to the Tits boundary of symmetric space.
Continuing the above analogy, the action of the mapping class group on Teichmüller space is analogous to the action of a nonuniform lattice on a symmetric space. Quasi-isometric rigidity was shown for nonuniform lattices in rank 1 groups other than \( \text{SL}(2, \mathbb{R}) \) and for some higher-rank lattices by Schwartz [25; 26], and in general by Eskin [6]. The quasi-isometric rigidity of the mapping class group \( \text{Mod}(S) \) was shown by Behrstock, Kleiner, Minsky and Mosher [1], by Hamenstädt [13] and later by Bowditch [4]. More generally, Bowditch in that same paper showed that if \( S \) and \( S' \) are closed surfaces with \( \xi(S) = \xi(S') \geq 4 \) and \( \phi \) is a quasi-isometric embedding of \( \text{Mod}(S) \) in \( \text{Mod}(S') \), then \( S = S' \) and \( \phi \) is a bounded distance from an isometry. He also shows quasi-isometric rigidity for Teichmüller space with the Weil–Petersson metric [2].

**Inductive step**

We prove this theorem inductively. To apply induction, we need to consider non-connected surfaces. Let \( \Sigma \) be a possibly disconnected surface of finite hyperbolic type. We always assume that \( \Sigma \) does not have a component that is a sphere, an annulus, a pair of pants or a torus. We define the complexity of \( \Sigma \) to be

\[
\xi(\Sigma) = 3g(\Sigma) + p(\Sigma) - 3c(\Sigma),
\]

where \( c(\Sigma) \) is the number of connected components of \( \Sigma \). For a point \( x \in \mathcal{T}(\Sigma) \), let \( P_x \) be the short pants decomposition at \( x \) and for a curve \( \gamma \in P_x \) define

\[
\tau_x(\gamma) \simeq \log \frac{1}{\text{Ext}_x(\gamma)},
\]

where \( \text{Ext}_x(\gamma) \) denotes the extremal length of the curve \( \gamma \) on the Riemann surface \( X \). (See Section 2.2 for exact definitions.) For a constant \( L > 0 \), consider the sets

\[
\mathcal{T}(\Sigma, L) = \{ x \in \mathcal{T}(\Sigma) \mid \tau_x(\gamma) \leq L \text{ for every curve } \gamma \},
\]

\[
\partial_L(\Sigma, L) = \{ x \in \mathcal{T}(\Sigma, L) \mid \tau_x(\gamma) = L \text{ for all } \gamma \in P_x \}.
\]

Thinking of \( L \) as a very large number, we say a quasi-isometry

\[
f_{\Sigma} : \mathcal{T}(\Sigma, L) \to \mathcal{T}(\Sigma, L)
\]

is \( C_{\Sigma} \)-anchored if the restriction of \( f_{\Sigma} \) to \( \partial_L(\Sigma) \) is nearly the identity. That is, for every \( x \in \partial_L(\Sigma, L) \),

\[
d_{\mathcal{T}(\Sigma)}(x, f_{\Sigma}(x)) \leq C_{\Sigma}.
\]

Our induction step is the following.
Theorem 1.2  Let $\Sigma$ be a surface of finite hyperbolic type. For every $K_\Sigma$ and $C_\Sigma$, there are $L_\Sigma$ and $D_\Sigma$ such that for $L \geq L_\Sigma$, if

$$ f_\Sigma : \mathcal{T}(\Sigma, L) \to \mathcal{T}(\Sigma, L) $$

is a $(K_\Sigma, C_\Sigma)$-quasi-isometry that is $C_\Sigma$-anchored, then for every $x \in \mathcal{T}(\Sigma)$ we have

$$ d_{\mathcal{T}(\Sigma)}(x, f_\Sigma(x)) \leq D_\Sigma. $$

Note that $D_\Sigma$ depends on the topology of $\Sigma$ and the constants $K_\Sigma$, $C_\Sigma$ and $L_\Sigma$, but is independent of $L$.

Outline of the proof

The overall strategy is to take the quasi-isometry and prove it preserves more and more of the structure of Teichmüller space. Section 2 is devoted to establishing notation and background material. In Section 3 we define the rank of a point as the number of short curves plus the number of complementary components that are not pairs of pants. A point has maximal rank if all complementary components $W$ have $\xi(W) \leq 1$. We show in Proposition 3.8 that a quasi-isometry preserves points with maximal rank. The proof uses the ideas of coarse differentiation, previously developed in the context of Teichmüller space in [11], which in turn is based on the work of Eskin, Fisher and Whyte [9; 10]. Coarse differentiation was also previously used by Peng [20; 21] to study quasiflats in solvable Lie groups. The important property of maximal rank is that near such a point of maximal rank, Teichmüller space is close to being isometric to a product of copies of $\mathbb{H}$, with the supremum metric; see Minsky [18].

In Section 4 we prove a local version of the splitting theorem shown in Kleiner and Leeb [16] in the context of symmetric spaces and later in Eskin and Farb [8] for products of hyperbolic planes. There it is proved in Theorem 4.1 that a quasi-isometric embedding from a large ball in $\prod \mathbb{H}$ to $\prod \mathbb{H}$ can be restricted to a smaller ball where it factors, up to a fixed additive error. This local factoring is applied in Section 5 to give a bijective association $f_x^*$ between factors at $x$ and at $f(x)$. We also prove a notion of analytic continuation, namely, we examine how $f_x^*$ and $f_{x'}^*$ are related when local factors around points $x$ and $x'$ overlap.

We use this to show (Proposition 6.1) that maximal cusps are preserved by the quasi-isometry. A maximal cusp is the subset of maximal rank consisting of points where there is a maximal set of short curves all about the same length. There Teichmüller
space looks like a cone in a product of horoballs inside the product of $\mathbb{H}$. The set of maximal cusps is disconnected; there is a component associated to every pants decomposition. Thus, $f$ induces a bijection on the set of pants decompositions. The next step is then to show this map is induced by automorphism of the curve complex, and hence by Ivanov’s theorem, it is associated to an isometry of Teichmüller space. Composing $f$ by the inverse, we can assume that $f$ sends every component of the set of maximal cusps to itself. An immediate consequence of this is that $f$ restricted to the thick part of Teichmüller space is a bounded distance away from the identity (Proposition 6.6). From this fact and again applying Propositions 5.1 and 5.3, we then show, in Proposition 6.9, that for any point in the maximal rank set, the shortest curves are preserved and in fact, for any shortest curve $\alpha$ at points $x$, one has $f_x^*(\alpha) = \alpha$.

This allows one to cut along the shortest curve, induce a quasi-isometry on Teichmüller space of lower complexity and proceed by induction. Most of the discussion above also applies for the disconnected subsurfaces. Hence, much of Sections 5 and 6 is written in a way to apply to both $T(S)$ and $T(\Sigma, L)$ settings. The induction step is carried out in Section 7.

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2 Background

The purpose of this section is to establish notation and recall some statements from the literature. We refer the reader to [14; 12] for basic background on Teichmüller theory and to [18; 23] for some background on the geometry of the Teichmüller metric.

For much of this paper, the arguments are meant to apply to both $T(S)$, which is the Teichmüller space of a connected surface, and to $T(\Sigma, L)$, where $\Sigma$ is disconnected and the space is truncated. In such situations, we use the notation $T$ to refer to either case and use the full notation where the discussion is specific to one case or the other. Similarly, $f$ denotes either a quasi-isometry $f_S$ of $T(S)$ or a quasi-isometry $f_\Sigma$ of $T(\Sigma, L)$. A similar convention is also applied to other notation as we suppress symbols $S$ or $\Sigma$ to unify the discussion in the two cases. For example, $K$ and $C$ could refer to $K_S$ and $C_S$ or to $K_\Sigma$ and $C_\Sigma$, and $\xi$ could refer to $\xi(S)$ or $\xi(\Sigma)$.
By a curve, we mean the free isotopy class of a nontrivial, nonperipheral simple closed curve in either \( S \) or \( \Sigma \). Also, by a subsurface we mean a free isotopy class of a subsurface \( U \), where the inclusion map induces an injection between the fundamental groups. We always assume that \( U \) is not a pair of pants. When we say \( \gamma \) is a curve in \( U \), we always assume that it is not peripheral in \( U \) (not just in \( S \)). We write \( \alpha \subset \partial U \) to indicate that the curve \( \alpha \) is a boundary component of \( U \).

## 2.1 Product regions

We often examine a point \( x \in \mathcal{T} \) from the point of view of its subsurfaces. For every subsurface \( U \), there is a projection map

\[
\psi_U: \mathcal{T} \to \mathcal{T}(U)
\]

defined using the Fenchel–Nielsen coordinates; see [18] for details. When the boundary of \( U \) is not short, these maps are not well-behaved. Hence, these maps should be applied only when there is an upper bound on the length of \( \partial U \); see below.

When \( U \) is an annulus, or when \( \xi(U) = 1 \), the space \( \mathcal{T}(U) \) can be identified with the hyperbolic plane \( \mathbb{H} \); however the Teichmüller metric differs from the usual hyperbolic metric by a factor of 2. We always assume that \( \mathbb{H} \) is equipped with this metric, which has constant curvature \(-4\). We denote the point \( \psi_U(x) \) simply by \( x_U \).

A decomposition of \( S \) is a set \( \mathcal{U} \) of pairwise disjoint subsurfaces of \( S \) that fill \( S \). Subsurfaces in \( \mathcal{U} \) are allowed to be annuli (but not pairs of pants). In this context, filling means that every curve in \( S \) either intersects or is contained in some \( U \in \mathcal{U} \). In particular, for every \( U \in \mathcal{U} \), the annulus associated to every boundary curve of \( U \) is also included in \( \mathcal{U} \). The same discussion holds for \( \Sigma \).

For a decomposition \( \mathcal{U} \) and \( \ell_0 > 0 \) define

\[
\mathcal{T}_{\mathcal{U}} = \{ x \in \mathcal{T} \mid \text{Ext}_x(\alpha) \leq \ell_0 \text{ for all } U \in \mathcal{U} \text{ and } \alpha \subset \partial U \}.
\]

**Theorem 2.1** (product regions theorem [18]) For \( \ell_0 \) small enough,

\[
\psi_{\mathcal{U}} = \prod_{U \in \mathcal{U}} \psi_U: \mathcal{T}_{\mathcal{U}} \to \prod_{U \in \mathcal{U}} \mathcal{T}(U)
\]

is an isometry up to a uniform additive error \( D_{pr} \). Here, the product on the right-hand side is equipped with the sup metric. That is, for \( x^1 \) and \( x^2 \),

\[
d_{\mathcal{T}}(x^1, x^2) - D_{pr} \leq \sup_{U \in \mathcal{U}} d_{\mathcal{T}(U)}(x^1_U, x^2_U) \leq d_{\mathcal{T}}(x^1, x^2) + D_{pr}.
\]

\[\text{(2)}\]

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For the rest of the paper, we fix a value for \( \ell_0 \) that makes this statement hold. We also assume that two curves of length less than \( \ell_0 \) do not intersect. We refer to \( T_\mathcal{U} \) as the product region associated to \( \mathcal{U} \).

A point \( x \in T_\mathcal{U} \) can be coarsely described by its projection \( \{x_U\}_{U \in \mathcal{U}} \). We often say “let \( x \in T_\mathcal{U} \) be a point whose projection to every \( U \in \mathcal{U} \) is a given point in \( T(U) \)”. Such a description does not determine \( x \) uniquely, but it does up to a distance of at most \( D_{pr} \).

We say \( \mathcal{U} \) is maximal if every \( U \in \mathcal{U} \) is either an annulus, or \( \xi(U) = 1 \) (recall that pairs of pants are always excluded). That is, if \( \mathcal{U} \) is maximal then the associated product region is isometric, up to an additive error \( D_{pr} \), to a subset of a product space \( \prod_{i=1}^\mathcal{U} \mathbb{H} \) equipped with the sup metric. For the rest of the paper, we always assume the product \( \prod_{i=1}^\mathcal{U} \mathbb{H} \) is equipped with the sup metric. For points \( x, y \in T(S) \), we say \( x \) and \( y \) are in the same maximal product region if there is a maximal decomposition \( \mathcal{U} \) with \( x, y \in T_\mathcal{U} \). Note that such a \( \mathcal{U} \) is not unique. For example, let \( P \) be a pants decomposition and let \( x \) be a point such that the length in \( x \) of every curve in \( P \) is less than \( \ell_0 \). Then there are many decompositions \( \mathcal{U} \) where every \( U \in \mathcal{U} \) is either a punctured torus or a four-times-punctured sphere with \( \partial U \subset P \) or an annulus whose core curve is in \( P \). The point \( x \) belongs to \( T_\mathcal{U} \) for every such decomposition \( \mathcal{U} \).

2.2 Short curves on a surface

The thick part \( T_{thick} \) of \( T \) is the set of points \( x \) for which \( \text{Ext}_x(\gamma) \geq \ell_0 \) for every curve \( \gamma \). There is a constant \( B \) (the Bers constant) such that for any point \( z \in T_{thick} \), the set of curves of extremal length at most \( B \) fills the surface. That is, every curve intersects a curve of length at most \( B \). Note that every \( x \in T \) contains a curve of

\[ \text{Figure 1: Two maximal decompositions } U_1 \text{ and } U_2 \text{ are depicted above. Note that } U_1 \cap U_2 = \emptyset. \text{ However, for the pants decomposition } P = \{\alpha, \beta, \gamma\}, \text{ any point } x \in T \text{ for which all curves in } P \text{ have a length less than } \ell_0 \text{ is contained in } T_{U_1} \cap T_{U_2}. \]
length at most \( B \). In fact, we choose \( B \) large enough so that every \( x \in T \) has a pants decomposition of length at most \( B \). We call such a pants decomposition the \textit{short pants decomposition at} \( x \) and denote it by \( P_x \). We also assume that \( \ell_0 \) is small enough that if \( \text{Ext}_{x}(\alpha) \leq \ell_0 \) (\( \alpha \) is \( \ell_0 \)-short) then \( \alpha \) does not intersect any \( B \)-short curve. Hence, \( P_x \) contains every \( \ell_0 \)-short curve.

It is often more convenient to work with the logarithm of length. For \( x \in T \) and \( \alpha \in P_x \), define \( \tau_x(\alpha) \) to be the largest number such that if \( d_T(x,x') \leq \tau_x(\alpha) \) then \( \text{Ext}_{x'}(\alpha) \leq \ell_0 \). From the product regions theorem, we have

\[
\left| \tau_x(\alpha) - \log \frac{1}{\text{Ext}_{x}(\alpha)} \right| = O(1),
\]

where the constant on the right-hand side depends on the value of \( D_{pr} \) and \( \log 1/\ell_0 \).

We often need to \textit{pinch} a curve. Let \( x \in T \) and \( \tau \) be given and let \( \alpha \in P_x \) with \( \tau_x(\alpha) = O(1) \). Let \( x' \) be a point with \( d_T(x,x') = O(1) \) and for which the length of \( \alpha \) is \( \ell_0 \). Let \( U = S - \alpha \) and let \( x'' \) be the point such that

\[
\tau_{x''}(\alpha) = \tau, \quad x'_U = x''_U, \quad \mathfrak{m}(x'_\alpha) = \mathfrak{m}(x''_\alpha).
\]

The last condition means \( x' \) and \( x'' \) have no relative twisting around \( \alpha \). We then say \( x'' \) is a point obtained from \( x \) by pinching \( \alpha \). There is a constant \( d_{\text{pinch}} \) such that

\[
\tau \leq d_T(x,x'') \leq \tau + d_{\text{pinch}}.
\]

2.3 Subsurface projection

Let \( U \) be a subsurface of \( S \) with \( \xi(U) \geq 1 \). Let \( \mathcal{C}(U) \) denote the curve graph of \( U \); that is, a graph where a vertex represents a curve in \( U \), and an edge represents a pair of disjoint curves. When \( \xi(U) = 1 \), the subsurface \( U \) does not contain disjoint curves. Here an edge is a pair of curves that intersect minimally; once in the punctured-torus case and twice in the four-times-punctured sphere case. In the case that \( U \) is an annulus with core curve \( \alpha \), in place of the curve complex we use the subset \( H_\alpha \subset T(U) \) of all points for which the extremal length of \( \alpha \) is at most \( \ell_0 \). This is a horoball in \( \mathbb{H} = T(U) \). Depending on context, we use the notation \( \mathcal{C}(U) \) or \( H_\alpha \).

There is a projection map

\[
\pi_U : \mathcal{T}(U) \to \mathcal{C}(U)
\]

that sends a point \( z \in \mathcal{T}(U) \) to a curve \( \gamma \) in \( U \) with \( \text{Ext}_z(\gamma) \leq B \). This is not unique but the image has a uniformly bounded diameter and hence the map is coarsely well-defined.
When $U$ is an annulus, $\pi_U(z)$ is the same as $\psi_U(z)$ if $\text{Ext}_z(\alpha) \leq \ell_0$ and, otherwise, is the point on the boundary of $H_\alpha$ where the real value is twisting of $z$ around $\alpha$. (See [23, Section 2] for the definition and discussion of twisting.)

We can also define a projection $\pi_U(\gamma)$, where $\gamma$ is any curve that intersects $U$ nontrivially. If $\gamma \subset U$ then choose the projection to be $\gamma$. If $\gamma$ is not contained in $U$ then $\gamma \cap U$ is a collection of arcs with endpoints on $\partial U$. Choose one such arc and perform a surgery using this arc and a subarc of $\partial U$ to find a point in $C(U)$. The choice of different arcs or different choices of intersecting pants curves determines a set of diameter 2 in $C(U)$; hence the projection is coarsely defined. Note that this is not defined when $\gamma$ is disjoint from $U$. We also define a projection $T(S) \to C(U)$ to be $\pi_U \circ \pi_S$, however we still denote it by $\pi_U$. For $x, y \in T$, we define

$$d_U(x, y) := d_{C(U)}(\pi_U(x), \pi_U(y)).$$

For curves $\alpha$ and $\beta$, $d_U(\alpha, \beta)$ is similarly defined.

In fact, the subsurface projections can be used to estimate the distance between two points in $T$; see [22]. There is a threshold $T$ such that

$$d_T(x, y) \geq \sum_{W \in \mathcal{W}_T} d_W(x, y),$$

where $\mathcal{W}_T$ is the set of subsurfaces $W$ where $d_W(x, y) \geq T$.

**Definition 2.2** We say a pair of points $x, y \in T(S)$ are $M$–cobounded relative to a subsurface $U \subset S$ if $\partial U$ is $\ell_0$–short in $x$ and $y$ and if $d_V(x, y) \leq M$ for every surface $V \neq U$. If $U = S$, we simply say $x$ and $y$ are $M$–cobounded.

Similarly, we say a pair of curves $\alpha, \beta$ in $U$ are $M$–cobounded relative to $U$ if for every $V \subset U$, we have $d_V(\alpha, \beta) \leq M$ when defined. If $U = S$, we simply say $\alpha$ and $\beta$ are $M$–cobounded.

A path $g$ in $T(S)$ or in $C(U)$ is $M$–cobounded relative to $U$ if every pair of points in $g$ are $M$–cobounded relative to $U$. Once and for all, we choose a constant $M$ so that through every point $x \in T(S)$ and for every $U$ whose boundary length is at most $\ell_0$ in $x$, there is a bi-infinite path in $T(S)$ passing through $x$ that is $M$–cobounded relative to $U$. One can, for example, take an axis of a pseudo-Anosov element in $T(U)$ and then use the product regions theorem to elevate that to a path in $T(S)$ whose projections to disjoint subsurfaces are constant. When we say a geodesic $g$ in $T(S)$ is cobounded
relative to $U$, we always mean that it is $M$–cobounded relative to $U$. From equation (3) (the distance formula) we have, for $x$ and $y$ along such $g$,

\begin{equation}
\frac{d_{\mathcal{T}}(x, y)}{d_U(x, y)} \gtrsim \frac{\pi_U(x, y)}{d_U(x, y)}.
\end{equation}

See below for the definition of the notation $\gtrsim$.

## 3 Rank is preserved

In this section, we recall some results from [11] and we develop them further to show that the set of points in Teichmüller space with maximum rank is coarsely preserved; see Proposition 3.8 below. Since the notation $\gtrsim$ and $\lessgtr$ were used in [11], we continue to use them in this section. Recall from [11] that $A \gtrsim B$ means there is a constant $C$, depending only on the topology of $S$ or $\Sigma$, such that $C^{-1} A \leq B \leq CA$. We say $A$ and $B$ are comparable. Similarly, $A \lessgtr B$ means there is a constant $C$, depending only on the topology of $S$ or $\Sigma$, such that $A - C \leq B \leq A + C$. We say $A$ and $B$ are the same up to an additive error. For the rest of the paper, we will name our constants explicitly, as we did with $D_{\text{pr}}$ and $d_{\text{pinch}}$. The only constant from this section that is used later is the constant $d_0$ from Proposition 3.8.

**Coarse differentiation and preferred paths**

A path $g: [a, b] \to \mathcal{T}$ is called a preferred path if, for every subsurface $U$, the image of $\pi_U \circ g$ is a reparametrized quasigeodesic in $C(U)$. We use preferred paths as coarse analogues of straight lines in $\mathcal{T}$. Teichmüller geodesics are examples of preferred paths, but the latter are much more general. One explanation of this greater generality is that given a pair of disjoint domains, a preferred path may move in the curve complex of each essentially arbitrarily as long as they are quasigeodesics, while Teichmüller geodesics move in a product region in a manner determined by the endpoints of the geodesic.

**Definition 3.1** A box in $\mathbb{R}^n$ is a product of intervals; namely $B = \prod_{i=1}^n I_i$, where $I_i$ is an interval in $\mathbb{R}$. We say a box $B$ is of size $R$ if $|I_i| \gtrsim R$ for every $i$ and if the diameter of $B$ is less than $R$. Note that if $B$ is of size $R$ and of size $R'$, then $R \lessgtr R'$. The box in $\mathbb{R}^n$ is always assumed to be equipped with the usual Euclidean metric.

For points $a, b \in B$, we often treat the geodesic segment $[a, b]$ in $B$ as an interval of times parametrized by $t$. A map $f: B \to \mathcal{T}$ from a box of size $R$ in $\mathbb{R}^n$ to $\mathcal{T}$ is called...
\(\epsilon\)-efficient if, for any pair of points \(a, b \in B\), there is a preferred path \(g: [a, b] \to T\) such that, for \(t \in [a, b]\),
\[
d_T(f(t), g(t)) \leq \epsilon R.
\]

Let \(B\) be a box of size \(L\) in \(\mathbb{R}^n\) and let \(B\) be a central sub-box of \(B\) with comparable diameter (say half). For any constant \(0 < R \leq \frac{1}{3} L\), let \(B_R\) be a subdivision of \(B\) into boxes of size \(R\). That is,

1. boxes in \(B_R\) are of size \(R\),
2. they are contained in \(B\) and hence their distance to the boundary of \(B\) is comparable to \(L\),
3. they have disjoint interiors and
4. \(|B_R|^* \approx (L/R)^n\).

The following combines Theorem 2.5 and Theorem 4.9 in [11].

**Theorem 3.2** (coarse differentiation) For every \(K, C, \epsilon, \theta\) and \(R_0\) there is an \(L_0\) such that the following holds. For \(L \geq L_0\), let \(f: B \to T\) be a \((K, C)\)-quasi-Lipschitz map, where \(B\) is a box of size \(L\) in \(\mathbb{R}^n\). Then, there is a size \(\frac{1}{3} L \geq R \geq R_0\) such that the proportion of boxes \(B' \in B_R\) where \(f|_{B'}\) is \(\epsilon\)-efficient is at least \((1 - \theta)\).

Even though we have no control over the distribution of efficient boxes, the following lemma says we can still connect every two points in \(B\) with a path that does not intersect too many nonefficient boxes.

**Lemma 3.3** Let \(L, R, B_R, \epsilon\) and \(\theta\) be as above. Then, for any pair of points \(a, b \in B\), there is a path \(\gamma\) in \(B\) connecting them so that \(\gamma\) is covered by at most \(O(L/R)\) boxes and the number of boxes in the covering that are not \(\epsilon\)-efficient is at most \((1 - \theta)\).

**Proof** Let \(N = \sqrt[3]{\theta L/R}\). First assume that the distance between \(a\) and \(b\) to the boundary of \(B\) is at least \(NR\). Consider the geodesic segment \([a, b]\). Take \((n-1)\)-dimensional totally geodesic boxes \(Q_a\) and \(Q_b\) containing \(a\) and \(b\) respectively that are perpendicular to \([a, b]\), parallel to each other and have a diameter \(NR\). Choose an \(R\)-net of points \(p_1, \ldots, p_k\) in \(Q_a\) and \(q_1, \ldots, q_k\) in \(Q_b\) so that \([p_i, q_i]\) is parallel to \([a, b]\). We have, for \(1 \leq i, j \leq k\),
\[
d_{\mathbb{R}^n}([p_i, q_i], [p_j, q_j]) > R \quad \text{and} \quad k^* \approx N^{n-1}.
\]
For $1 \leq i \leq k$, let $\gamma_i$ be the path that is a concatenation of geodesic segments $[a, p_i]$, $[p_i, q_i]$ and $[q_i, b]$. We claim one of these paths satisfies the conclusions of the lemma.

Assume, for the sake of contradiction, that the number of nonefficient boxes along each $\gamma_i$ is larger than $cN$ for some large $c > 0$. Then the total number of nonefficient boxes is at least

$$kcN = cN^n = c \theta \left( \frac{L}{R} \right)^n.$$ 

But this is not possible for large enough values of $c$; see property (4) of $B_R$ above and Theorem 3.2. Hence, there is a $c = O(1)$ such that $[p_i, q_i]$ intersects at most $cN$ nonefficient boxes.

Note that the segments $[a, p_i]$ and $[q_i, b]$ intersect at most $N$ boxes each. Hence, the number of inefficient boxes intersecting $\gamma_i$ is at most $(c + 2)N$. In the case that $a$ or $b$ are close to the boundary, we choose points $a'$ and $b'$ nearby (distance $NR$) and apply the above argument to find an appropriate path between $a'$ and $b'$ and then concatenate this path with segments $[a, a']$ and $[b, b']$. The total number of inefficient boxes along this path is at most $(c + 4)N$. This finishes the proof.

\[\square\]

**Efficient quasi-isometric embeddings**

In this section, we examine efficient maps that are also assumed to be quasi-isometric embeddings. We will show that they have maximal rank; they make small progress in any subsurface $W$ with $\xi(W) \geq 2$.

**Definition 3.4** Let $U$ be a decomposition of $S$. For every $U \in \mathcal{U}$, let $g_U: I_U \to \mathcal{T}(U)$ be a preferred path. Consider the box $B = \prod_U I_U \subset \mathbb{R}^m$, where $m$ is the number of elements in $U$. Consider the map

$$F: B \to \mathcal{T}_U = \prod_{U \in \mathcal{U}} \mathcal{T}(U), \quad \text{where} \quad F = \prod_{U \in \mathcal{U}} g_U.$$ 

Then $F$ is a quasi-isometric embedding because each $g_U$ is a quasigeodesic. We call this map a standard flat in $\mathcal{T}_U$. The dimension of a standard flat is defined to be the number of elements in $U$. The maximal dimension is $\xi$.

The map $\bar{f}$ below will be a modified version of our map $f$ from Theorem 1.1. The next theorem is a basic tool. It says that if a large box of maximal dimension is quasi-isometrically embedded and mapped efficiently, then the projection to a cobounded geodesic in any subsurface must have small diameter.
Theorem 3.5  For every $K$, $C$ and $M$, there is an $\epsilon$ and $R_0$ such that the following holds. Let $\tilde{f} : B \to T(S)$ be an $\epsilon$–efficient $(K,C)$–quasi-isometric embedding defined on a box $B \subset \mathbb{R}^\xi$ of size $R \geq R_0$, let $\omega_0$ be a $M$–cobounded geodesic in $C(W)$, where $W$ is a subsurface with $\xi(W) \geq 2$, and let $\pi_{\omega_0}$ be the closest-point projection map from $C(W)$ to $\omega_0$. Define

$$\pi = \pi_{\omega_0} \circ \pi_W \circ \tilde{f}.$$  

Then, for all points $a, b \in B$, we have

$$d_W(\pi(a), \pi(b)) \leq \sqrt{\epsilon}R.$$  

Proof  Assume by way of contradiction that for all large $R$ and all small $\epsilon$ there is a subsurface $W$, $\xi(W) \geq 2$, an $M$–cobounded geodesic $\omega_0$ in $C(W)$, a box $B$ of size $R$ in $\mathbb{R}^m$, an $\epsilon$–efficient map $\tilde{f} : B \to T$ and a pair of points $a, b \in B$ such that

$$(5) \quad d_W(\pi(a), \pi(b)) \geq \sqrt{\epsilon}R.$$  

Let $g : [a, b] \to T$ be the preferred path joining $\tilde{f}(a)$ and $\tilde{f}(b)$ coming from the efficiency assumption. Since $g$ is a preferred path, if $\omega$ is a geodesic in $C(W)$ joining $\pi_W(\tilde{f}(a))$ and $\pi_W(\tilde{f}(b))$, then $\omega$ can be reparametrized so that

$$d_W(g(t), \omega(t)) = O(1).$$  

As stated in equation (5), we are assuming that the projection of the geodesic $\omega$ to $\omega_0$ has a length of at least $\sqrt{\epsilon}R$.

The hyperbolicity of $C(W)$ implies that $\omega$ and therefore $\pi_W \circ g$ lie in a uniformly bounded neighborhood of $\omega_0$ along a segment of $g$ of length $\asymp \sqrt{\epsilon}R$. Divide this piece of $\omega_0$ into three segments. Let $\alpha_1, \alpha_2, \alpha_3, \alpha_4 \in C(W)$ be the corresponding endpoints of these segments, which for $i = 1, 2, 3$ satisfy

$$(6) \quad d_W(\alpha_i, \alpha_{i+1}) \asymp \sqrt{\epsilon}R.$$  

Let $\omega_{\text{mid}} = [\alpha_2, \alpha_3]$ be the middle segment, let $[c, d] \subset [a, b]$ be the associated time interval and let $g_{\text{mid}} = g|_{[c, d]}$.

Step 1  We claim that for every $V$ such that $V \cap W \neq \emptyset$ (that is, either $V \subset W$ or $V \nmid W$), the image of the projection of $g_{\text{mid}}$ to $C(V)$ has a bounded diameter. Note that, since $g$ is a preferred path, it is enough to prove either $d_V(\alpha_2, \alpha_3)$ or $d_V(\alpha_1, \alpha_4)$ is uniformly bounded, assuming those curves intersect $V$.  

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We argue in two cases. If every curve in $[\alpha_2, \alpha_3]$ intersects $V$, the claim follows from the bounded geodesic image theorem [17, Theorem 3.1]. Otherwise, $\partial V$ is close in $C(W)$ to this segment and hence it is far in $C(W)$ from curves $\alpha_1$ and $\alpha_4$. Let $\alpha_1$ and $\alpha_4$ be curves on $\omega_0$ that are close to $\alpha_1$ and $\alpha_4$, respectively. Then, $\partial V$ intersects every curve in $[\alpha_1, \alpha_4]$ and, by the bounded geodesic image theorem, the projections of these segments to $C(V)$ have bounded diameters. But $\omega_0$ is cobounded. Hence, $d_V(\alpha_1, \alpha_4) = O(1)$ and therefore $d_V(\alpha_1, \alpha_4) = O(1)$. This proves the claim.

**Step 2** To obtain a contradiction, we will find a large sub-box of $B$ that maps near a standard flat $F$ of maximal rank.

Note that the map $\pi$ above is quasi-Lipschitz. Choose a constant $D$ which is large compared to the quasi-Lipschitz constant of $\pi$ and the hyperbolicity constant of $C(W)$. Let $a', b'$ be points in $B$ in a neighborhood of $a, b$, respectively, such that

$$\|a - a'\| \leq \frac{\sqrt{\epsilon} R}{D} \quad \text{and} \quad \|b - b'\| \leq \frac{\sqrt{\epsilon} R}{D}. \quad (7)$$

Let $g'$ be the preferred path joining $\bar{f}(a'), \bar{f}(b')$ and $\omega'$ be the geodesic in $C(W)$ connecting $\pi_W(\bar{f}(a'))$ to $\pi_W(\bar{f}(b'))$. Consider the quadrilateral

$$\beta = \pi_W(\bar{f}(a)), \quad \gamma = \pi_W(\bar{f}(b)), \quad \beta' = \pi_W(\bar{f}(a')), \quad \gamma' = \pi_W(\bar{f}(b'))$$

in $C(W)$. From the assumption on $D$, the edges $[\beta, \beta']$ and $[\gamma, \gamma']$ are short compared to $[\beta, \gamma]$. From the hyperbolicity of $C(W)$, we conclude that $\omega'$ has a subsegment $\omega_{\text{mid}}'$ that has a bounded Hausdorff distance to $\omega_{\text{mid}}$. Let $g'_{\text{mid}}$ be the associated subsegment of $g'$ (see previous step). As we argued in the previous step, the projection of $g'_{\text{mid}}$ to $C(V)$ has a bounded diameter for every $V \cap W = \emptyset$. In fact, it is close to the projection of $g_{\text{mid}}$ to $C(V)$.

The union of subsegments of type $[a', b']$ fill a $(\sqrt{\epsilon} R/D)$–neighborhood of $[c, d]$ and

$$|d - c| \leq \sqrt{\epsilon} R.$$ 

Therefore, there is a subbox $B' \subset B$ of size $R' < \sqrt{\epsilon} R$ such that $(\pi_V \circ \bar{f})(B')$ has bounded diameter for every $V \cap W = \emptyset$. For $\epsilon_0$ small to be chosen later (it will depend only on universal constants), set $\epsilon_0 = \epsilon_0^k$ and assume $\epsilon$ is small enough so that

$$\sqrt{\epsilon} < \epsilon \epsilon_0^k.$$ 

Since $f$ is $\epsilon$–efficient and $\epsilon < \epsilon \epsilon_0^k$ it is $\epsilon \epsilon_0^k$–efficient. By Theorem 7.2 of [11] (which can be applied if $R$ is large enough) there is a sub-box $B'' \subset B'$ of size $R'' \geq \epsilon \epsilon_0^k R'$ such
that $\tilde{f}(B'')$ is within $O(\epsilon_0 R'')$ of a standard flat $F$. The implied constants depend only on $K, C$ and $\xi$.

We show this is impossible for $\epsilon_0$ sufficiently small. Note that $\xi$ is the maximum dimension of any standard flat. Since $B''$ is a box of dimension $\xi$ and $\tilde{f}$ is a quasi-isometric embedding, the standard flat $F$ must have dimension $\xi$ as well. Let $\mathcal{V}$ be the decomposition of $S$ with $|\mathcal{V}| = \xi$, and let $F_{\mathcal{V}}: I_{\mathcal{V}} \to T(\mathcal{V})$ be the preferred paths, where

$$F: \prod_{\mathcal{V} \in \mathcal{V}} I_{\mathcal{V}} \to T.$$  

Then $\tilde{f}(B'')$ is contained in the $O(\epsilon_0 R'')$–neighborhood of the image of $F$. We assume $I_{\mathcal{V}}$ is the smallest possible interval for which this holds. Then, for $V \in \mathcal{V}$, $F_{\mathcal{V}}(I_{\mathcal{V}})$ has a diameter comparable to $R''$, which is the size of $B''$.

Since $|\mathcal{V}| = \xi$, every $V \in \mathcal{V}$ is either an annulus or $\xi(V) = 1$. Hence, they cannot equal $W$ and, for at least one $V \in \mathcal{V}$, we have $V \cap W \neq \emptyset$. In fact, we can assume $V$ is an annulus, because $\mathcal{V}$ is maximal and if a subsurface is in $\mathcal{V}$ the annuli associated to its boundary curves are also in $\mathcal{V}$.

From the assumption of the minimality of lengths of $I_{\mathcal{V}}$, we know that every $t_{\mathcal{V}} \in I_{\mathcal{V}}$ can be completed to a vector in $\prod_{\mathcal{V} \in \mathcal{V}} I_{\mathcal{V}}$ whose image is in the $O(\epsilon_0 R'')$–neighborhood of $\tilde{f}(B'') \subset \tilde{f}(B')$. In addition, since $\tilde{f}$ is $\epsilon$–efficient, any point in $\tilde{f}(B')$ is $\epsilon R$–close to some $g'_{\text{mid}}$. We already know that for any such $V$ the projection of $g'_{\text{mid}}$ to $C(V)$ is $O(1)$. Combining these statements we find that the projection of the image of $F$ to $C(V)$ of any such $V$ has a diameter $O(\epsilon R + \epsilon_0 R'')$. This means the same bound also holds for the diameter of the projection to $T(\mathcal{V})$; in the case where $V$ is an annulus and $\partial V$ is short, the two distances are the same. We have shown

$$R'' \preceq \text{diam}_{T(\mathcal{V})}(F_{\mathcal{V}}(I_{\mathcal{V}})) \preceq \epsilon R + \epsilon_0 R''.$$  

Therefore, $R'' \preceq \epsilon R$. But

$$R'' \geq \epsilon \xi R' \geq \epsilon \xi \sqrt{\epsilon} R \geq \frac{\epsilon R}{\epsilon_0}.$$  

For $\epsilon_0$ sufficiently small, this is a contradiction. That is, the theorem holds for appropriate values of $\epsilon$ and $R_0$. \hfill \Box

**Maximal rank is preserved**

Recall that, for $x \in T(S)$ and a curve $\alpha$, $\tau_x(\alpha)$ is the largest number such that if $d(x, x') \leq \tau_x(\alpha)$ then $\text{Ext}_{x'}(\alpha) \leq \ell_0$. 

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For a point \( x \) in \( T(S) \), let \( S_x = S_x(\ell_0) \) be the set of curves \( \alpha \) such that \( \text{Ext}_x(\alpha) \leq \ell_0 \).

**Definition 3.6** A point \( x \in T(S) \) has maximal rank when the components of \( S \setminus S_x \) are all either a pair of pants, a once-punctured torus or a four-times-punctured sphere. Denote the set of points with maximal rank by \( T_{\text{MR}} \). Let \( T_{\text{LR}} \) be its complement; the set with lower rank.

**Definition 3.7** Suppose \( x \in T_{\text{MR}} \). We say a curve \( \alpha \in S_x \) is isolated if by increasing its length to \( \ell_0 \) while keeping all other lengths the same one leaves \( T_{\text{MR}} \). A pair of curves in \( S_x \) are called adjacent if increasing both of their lengths to \( \ell_0 \) one leaves \( T_{\text{MR}} \).

The importance of this definition is that if \( d(x, T_{\text{LR}}) \geq d_0 \), then every isolated curve \( \alpha \) satisfies \( \tau_x(\alpha) \geq d \), and for any pair of adjacent curves \( \alpha_1, \alpha_2 \), at least one of them satisfies \( \tau_x(\alpha_i) \geq d \).

**Proposition 3.8** There exists a \( d_0 > 0 \) such that given \( x \in T \), if \( d(x, T_{\text{LR}}) \geq d_0 \) then \( f(x) \in T_{\text{MR}} \).

**Proof** Suppose by way of contradiction that, for large \( d_0 \), we have a point \( x \) such that \( d(x, T_{\text{LR}}) \geq d_0 \) but \( f(x) \in T_{\text{LR}} \). Then there is a surface \( W \) (possibly the whole surface) with \( \xi(W) \geq 2 \) such that the boundary curves of \( W \) are \( \ell_0 \)-short on \( f(x) \), but no curve in \( W \) is shorter than \( \ell_0 \) on \( f(x) \).

Let \( g_0 \) be a path passing through \( f(x) \) that is \( M \)-cobounded relative to \( W \); see the discussion after Definition 2.2. Let \( f(y) \) be a point in \( g_0 \) such that the distance in \( T \) between \( f(x) \) and \( f(y) \) is \( L = d_0/2K - C \). Since \( g_0 \) is \( M \)-cobounded, from equation (4) we have

\[
d_W(f(x), f(y)) \geq L.
\]

Since \( f \) is a \((K, C)\)-quasi-isometry, solving equation (1) for \( d(x, y) \) we get

\[
\frac{d_0}{2K^2} - \frac{2C}{K} \leq d(x, y) \leq \frac{d_0}{2}.
\]

In particular, \( y \in T_{\text{MR}} \).

Note that, in addition, for \( d_0 \geq 2 \log(1/\ell_0) \), there is a maximal product region \( T_U \) containing both \( x \) and \( y \). For \( d_T(x, T_{\text{LR}}) \geq d_0 \) implies that there is a set of curves \( \alpha \) such that \( \tau_x(\alpha) \geq d_0 \) for \( \alpha \in \alpha \), and such that the complementary regions have
complexity at most one. For all these curves, we have \( \tau_y(\alpha) \geq \frac{1}{2} d_0 \); in particular they are at least \( \ell_0 \) short in \( y \). This means both \( x \) and \( y \) are in \( \mathcal{T}_{\mathcal{U}} \).

In fact, there is a box

\[
B = \prod_{U \in \mathcal{U}} I_U \subset \mathbb{R}^\xi
\]

of size \( L \) and a quasi-isometry

\[
Q = \prod_{U \in \mathcal{U}} Q_U: B \to \mathcal{T}
\]

such that each \( Q_U: I_U \to T(U) \) is a geodesic and \( x \) and \( y \) are contained in \( Q(B) \) (recall that \( B \) is the central sub-box of half the diameter). The map \( Q \) is a quasi-isometry because \( B \) is equipped with the Euclidean metric and \( T_{\mathcal{U}} \) is equipped with the sup metric up to an additive error of \( D_{pr} \). Define

\[
f: B \to \mathcal{T} \quad \text{by} \quad f = f \circ Q.
\]

Then \( f \) is a \((K, C)\)–quasi-isometric embedding, where \( K \) and \( C \) depend on \( K \), \( C \) and the complexity \( \xi = |\mathcal{U}| \). (\( D_{pr} \) depends only on these constants.)

Let \( \omega_0 \) be the geodesic in \( \mathcal{C}(U) \) that fellow-travels the projection \( \pi_U(g_0) \). Then \( \omega_0 \) is \( M \)–cobounded with \( M \) slightly larger than \( M \). Define

\[
\pi = \pi_{\omega_0} \circ \pi_U \circ f,
\]

and let \( l_{\pi} \overset{\approx}{=} K \) be the Lipschitz constant of \( \pi \).

Let \( \epsilon \) and \( R_0 \) be constants from Theorem 3.5 associated to \( K \), \( C \) and \( M \) and choose \( \theta \) so that \( \xi / \theta l_{\pi} \) is small (see below). Then, let \( L_0 \) be the constant given by Theorem 3.2 (the dimension \( n \) equals \( \xi \)). Choose \( d_0 \) large enough that

\[
L = d(x, y) \geq \frac{d_0}{2K^2} - \frac{2C}{K} \geq L_0.
\]

Applying Theorem 3.2 to \( B \), we conclude that there is a scale \( R \) and a decomposition \( B_B \) of \( B \) to boxes of size \( R \) so that a proportion at least \((1 - \theta)\) of boxes in \( B_B \) are \( \epsilon \)–efficient.

By Lemma 3.3, there exists a path \( \gamma \) joining \( x \) to \( y \) that is covered by at most \( O(L/R) \) boxes in \( B_B \) of which at most \( O(\xi/\theta L/R) \) are not \( \epsilon \)–efficient.

Assume \( \gamma \) intersects boxes \( B_1, \ldots, B_k \) and let \( \gamma_i \) be the subinterval of \( \gamma \) associated to \( B_i \). By the triangle inequality, the sum of the diameters of \( \pi(\gamma_i) \) is larger
than $d_W(f(x), f(y))$, which is $\gtrsim L$ by equation (8). However, by Theorem 3.5,

\begin{equation}
\sum_{B_i \text{ is efficient}} \text{diam}_{\mathcal{C}(W)}(y_i) \gtrsim \frac{L}{R} \sqrt{e} R = \sqrt{e} L.
\end{equation}

The assumption on the number of nonefficient boxes gives

\begin{equation}
\sum_{B_i \text{ is not efficient}} \text{diam}_{\mathcal{C}(W)}(y_i) \gtrsim \left(\sqrt{\theta}\frac{L}{R}\right) l_\pi R = \sqrt{\theta} l_\pi L.
\end{equation}

For $\epsilon$ and $\theta$ small enough, equations (9) and (10) contradict the fact that the sum of the diameters is $\gtrsim L$. This finishes the proof. \hfill \Box

4 Local splitting theorem

In this section, we prove a local version of a splitting theorem proven by Kleiner and Leeb [16] and Eskin and Farb [8].

**Theorem 4.1** For every $K, C, \rho$ there are constants $R_0, D$ and $\rho$ such that for all

$$z = (z_1, \ldots, z_m) \in \prod_{i=1}^m \mathbb{H}_i$$

and $R \geq R_0$, the following holds. Let $B_R(z)$ be a ball of radius $R$ centered at $z$ in $\prod_{i=1}^m \mathbb{H}_i$ and let $\bar{f}: B_R(z) \to \prod_{i=1}^m \mathbb{H}_i$ be a $(K, C)$--quasi-isometric embedding whose image coarsely contains a ball of radius $\rho R$ about $\bar{f}(z)$. Then there is a smaller ball $B_{\rho R}(z)$, a permutation $\sigma: \{1, 2, \ldots, m\} \to \{1, 2, \ldots, m\}$ and $(K, C)$--quasi-isometric embeddings

$$\phi_i: B_{\rho R}(z_i) \to \mathbb{H}_{\sigma(i)}$$

such that the restriction of $\bar{f}$ to $B_{\rho R}(z)$ is $D$--close to

$$\phi_1 \times \cdots \times \phi_m: B_{\rho R}(z) \to \prod_{i=1}^m \mathbb{H}_{\sigma(i)}.$$

**Remark 4.2** When we use this theorem in Section 5, we need to equip $\prod \mathbb{H}$ with the $L^\infty$--metric. However, it is more convenient to use the $L^2$--metric for the proof. Note that if $\bar{f}$ is a quasi-isometry with respect to one metric, it is also a quasi-isometry with respect to the other. For the rest of this section, we assume $\prod \mathbb{H}$ is equipped with the $L^2$--metric. To simplify notation, we use $d_{\mathbb{H}}$ to denote the distance in both in $\mathbb{H}$ and in $\prod \mathbb{H}$.

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For the proof, we will use the notion of an asymptotic cone. Our brief discussion is taken from [16]. A nonprincipal ultrafilter is a finitely additive probability measure \( \omega \) on the subsets of the natural numbers \( \mathbb{N} \) such that

- \( \omega(S) = 0 \) or 1 for every \( S \subset \mathbb{N} \),
- \( \omega(S) = 0 \) for every finite subset \( S \subset \mathbb{N} \).

Given a bounded sequence \( \{a_n\} \) in \( \mathbb{R} \), there is a unique limit point \( a_\omega \in \mathbb{R} \) such that for every neighborhood \( U \) of \( a_\omega \), the set \( \{n \mid a_n \in U\} \) has full \( \omega \) measure. We write \( a_\omega = \omega \text{-lim } a_n \).

Let \( (X_n, d_n, *_n) \) be a sequence of metric spaces with basepoints. Consider

\[
X_\infty = \{ \bar{x} = (x_1, x_2, \ldots) \in \prod X_i \mid d_i(x_i, *_i) \text{ is bounded} \}.
\]

Define \( \tilde{d}_\omega : X_\infty \times X_\infty \to \mathbb{R} \) by

\[
\tilde{d}_\omega(\bar{x}, \bar{y}) = \omega \text{-lim } d_i(x_i, y_i).
\]

Now \( \tilde{d}_\omega \) is a pseudodistance. Define the ultralimit of the sequence \( (X_n, d_n, *_n) \) to be the quotient metric space \( (X_\omega, d_\omega) \) identifying the points of distance zero.

Let \( X' \) be a metric space and \( * \) be a basepoint. The asymptotic cone \( \text{Cone}(X') \) of \( X' \), with respect to the nonprincipal ultrafilter \( \omega \) and the sequence \( \lambda_n \) of scale factors with \( \omega \text{-lim } \lambda_n = \infty \) and the basepoint \( * \), is defined to be the ultralimit of the sequence of rescaled spaces \( (X_n, d_n, *_n) := (X', (1/\lambda_n)d_n, *) \). The asymptotic cone is independent of the basepoint.

In the case of \( \mathbb{H} \), the asymptotic cone \( \mathbb{H}_\omega \) is a metric tree which branches at every point, and the asymptotic cone \( (\prod_{i=1}^m \mathbb{H})_\omega \) of the product of hyperbolic planes is \( \prod_{i=1}^m \mathbb{H}_\omega \), the product of the asymptotic cones. A flat in \( \prod_{i=1}^m \mathbb{H} \) is a product \( \prod_{i=1}^m g_i \), where \( g_i \) is a geodesic in the \( i \text{th} \) factor.

We first prove a version of Theorem 4.1 with small linear error term. We then show that, by taking an even smaller ball, the error term can be made to be uniform additive.

**Proposition 4.3** Given \( K, C, \bar{\rho} \) there exist \( \rho' > 0 \) and \( D_0 \) such that for all sufficiently small \( \epsilon > 0 \), there exists an \( R_0 \) such that if \( R \geq R_0 \) and \( \tilde{f} \) is a \((K, C)\)-quasi-isometric embedding defined on \( B_R(z) \) with \( \tilde{f}(B_R(z)) \) \( C \)-coarsely containing \( B_{\bar{\rho}R}(\tilde{f}(z)) \), then:
• There is a permutation $\sigma$ and, for $1 \leq i \leq m$, there is a quasi-isometric embedding $\phi^*_i : B_{\rho'} R(z_i) \to \mathbb{H}_{\sigma(i)}$ such that, for

$$\phi^* = \phi^*_1 \times \cdots \times \phi^*_m : B_{\rho'} R(z) \to \prod_{i=1}^m \mathbb{H}$$

and for $x \in B_{\rho'} R(z)$, we have

$$d_\mathbb{H}(\bar{f}(x), \phi^*(x)) \leq \epsilon d_\mathbb{H}(z, x) + D_0. \quad (11)$$

• For any $x \in B_{\rho'} R(z)$ and any flat $F_x$ through $x$, there is a flat $F'_x$ such that for $p \in N_{\rho'} R(x) \cap F_x$,

$$d_\mathbb{H}(\bar{f}(p), F'_x) \leq m\epsilon d_\mathbb{H}(x, p) + D_0.$$

**Proof** We begin with a claim.

**Claim** Assume, for given $\epsilon$ and $D_0$, that there is a permutation $\sigma$ and a constant $\rho'$ so that, if $x, y \in B_{\rho'} R(z)$ differ only in the $i^{th}$ factor, then $\bar{f}(x)$ and $\bar{f}(y)$ differ in all factors besides the $\sigma(i)^{th}$ factor by at most $\frac{1}{m}(\epsilon d_\mathbb{H}(y, x) + D_0)$. Then the first conclusion holds.

**Proof of claim** For $x \in B_{\rho'} R(z_i)$ and an index $i$ define $z^i_x$ to be a point whose $i^{th}$ coordinate is $x$ and whose other coordinates are the same as the coordinates of $z$. We then define the map $\phi^*_i$ by letting $\phi^*_i(x)$ be the $i^{th}$ coordinate of $\bar{f}(z^i_x)$. We show that $\phi^*_i$ is a quasi-isometric embedding. For $x, x' \in B_{\rho'} R(z_i)$,

$$d_\mathbb{H}(\phi^*_i(x), \phi^*_i(x')) \leq d_\mathbb{H}(\bar{f}(z^i_x), \bar{f}(z^i_{x'})) \leq Kd_\mathbb{H}(z^i_x, z^i_{x'}) + C \leq Kd_\mathbb{H}(x, x') + C.$$

In addition, since $z^i_x$ and $z^i_{x'}$ differ in only one factor, for $\epsilon \leq \frac{1}{2K}$,

$$d_\mathbb{H}(\phi^*_i(x), \phi^*_i(x')) \geq d_\mathbb{H}(\bar{f}(z^i_x), \bar{f}(z^i_{x'})) - (m-1)\frac{\epsilon d_\mathbb{H}(z^i_x, z^i_{x'}) + D_0}{m}
\geq \frac{d_\mathbb{H}(z^i_x, z^i_{x'})}{K} - C - \epsilon d_\mathbb{H}(z^i_x, z^i_{x'}) - D_0
\geq \frac{d_\mathbb{H}(x, x')}{2K} - (C + D_0).$$

Hence, $\phi^*_i$ is a $(2K, C + D_0)$--quasi-isometry. Equation (11) follows from applying the triangle inequality $m$ times.

Now, suppose the first conclusion is false. Then there exist $K, C, \epsilon > 0$, sequences $\rho_n \to 0$ and $D_n \to \infty$, and a sequence $\bar{f}_n$ of $(K, C)$--quasi-isometric embeddings

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defined on the balls $B_{R_n}(z_n)$, with $R_n \to \infty$, such that the restriction of $f_n$ to $B_{\rho_n R_n}(z_n)$ does not factor as above. Then, by the above claim, there exist points $x_n, y_n$ in $B_{\rho_n R_n}(z_n)$ which differ in one factor only, and are such that $f_n(x_n)$ and $f_n(y_n)$ differ in at least two factors by an amount that is at least $(\epsilon d_{\mathbb{H}}(y_n, x_n) + D_n)/m$ in each. We can assume $d_{\mathbb{H}}(y_n, x_n) \to \infty$, for otherwise $d_{\mathbb{H}}(f(y_n), f(x_n))$ is bounded.

Let $\lambda_n = 1/d_{\mathbb{H}}(y_n, x_n)$ and scale the metric on $B_{R_n}(z_n)$ with basepoint $z_n$ by $\lambda_n$. Since $\rho_n \to 0$, we have $\lambda_n R_n \geq 1/2 \rho_n \to \infty$. That is, the radius of $B_{R_n}(z_n)$ in the scaled metric still goes to $\infty$. However, in the scaled metric, the distance between $x_n$ and $y_n$ equals 1. Let $\prod_{i=1}^m \mathbb{H}_\omega$ be the asymptotic cone of $\prod_{i=1}^m \mathbb{H}$ with basepoint $z_n$ and metric $d_n = \lambda_n d_{\mathbb{H}}$. For any $(u_1, u_2, \ldots) \in \prod_{i=1}^m \mathbb{H}_\omega$ we define

$$f_\omega : \prod_{i=1}^m \mathbb{H}_\omega \to \prod_{i=1}^m \mathbb{H}_\omega, \quad f_\omega(u_1, u_2, \ldots) = (f_1(u_1), f_2(u_2), \ldots) .$$

By definition $\lambda_n d_{\mathbb{H}}(u_n, z_n)$ is bounded, so for $n$ large enough, $u_n \in B_{R_n}(z_n)$ and $f_n(u_n)$ is defined. It is clear that $f_\omega$ is bi-Lipschitz. We show $f_\omega$ is onto.

By assumption $f_n(B_{R_n}(z_n))$ $C$–coarsely contains $B_{\bar{\rho}R_n}(f_n(z_n))$. Consider a point

$$(w_1, w_2, \ldots) \in \prod_{i=1}^m \mathbb{H}_\omega .$$

Since $\lambda_n d_{\mathbb{H}}(f_n(z_n), w_n)$ is bounded, for $n$ large enough, $w_n \in B_{\bar{\rho}R_n}(f_n(z_n))$. This means there is a sequence $u_n \in B_{R_n}(z_n)$ such that

$$d_{\mathbb{H}}(f_n(u_n), w_n) \leq C .$$

But $\lambda_n \to \infty$. Thus,

$$(w_1, w_2, \ldots) = f_\omega(u_1, u_2, \ldots) ,$$

and so $f_\omega$ is onto and hence a homeomorphism.

By the argument in Step 3 of Section 9 in [16], the map $f_\omega$ factors. The $\omega$–limit points of $x_n$ and $y_n$ give a pair of points $x_\omega$ and $y_\omega$ in $\prod_{i=1}^m \mathbb{H}_\omega$ that have the same coordinate in every factor but one, and satisfy

$$d_{\mathbb{H}_\omega}(x_\omega, y_\omega) = 1 .$$

but $f_\omega(x_\omega)$ and $f_\omega(y_\omega)$ differ in at least two coordinates by at least $\epsilon/m$. This contradicts the fact that $f_\omega$ factors. This contradiction proves the first conclusion.
We now use the first conclusion to prove the second conclusion. Let \( r' = \rho' R \). Consider a flat \( F_x \) through \( x \) and let \( g_i = [a_i, b_i] \) be a geodesic in the \( i \)th factor such that
\[
F_x \cap B_r(x) \subseteq \prod_{i=1}^m [a_i, b_i].
\]
Let \( g'_i \) be the geodesic joining \( \phi^*_i(a_i) \) to \( \phi^*_i(b_i) \). Since \( \phi^*_i \) is a quasi-isometric embedding,
\[
d_\mathbb{H}(\phi^*_i(g_i), g'_i) = O(1),
\]
where the bound depends on \( K, C, D_0 \). Let \( F_0 \) be the flat determined by the \( g'_i \). For a point \( p \in F \cap B_r(x) \), the \( i \)th coordinate of \( p \) lies on \( g_i \). Therefore, the \( i \)th coordinate of \( f(p) \) is distance at most \( \epsilon d(x, p) \) from a point whose \( i \)th coordinate lies on \( \phi^*_i(g_i) \) and that in turn is distance \( O(1) \) from \( g'_i \). Since this is true for each \( i \), the triangle inequality implies that
\[
d_\mathbb{H}(f(p), F') \leq m\epsilon d_\mathbb{H}(x, p) + O(1).
\]

**Lemma 4.4** Fix a constant \( \rho'' < 1 \). There exists a \( D'' \) such that for all sufficiently small \( \epsilon \) and large \( R' \) the following holds. Suppose \( F, F' \) are flats, \( p \in F \) and
\[
B_{R'}(p) \cap F \subset N_{\epsilon R'}(F').
\]
Then, for \( r \leq \rho'' R' \),
\[
B_r(p) \cap F \subset N_{D''}(F').
\]

**Proof** We can assume \( \epsilon R' \) is larger than the hyperbolicity constant for \( \mathbb{H} \). Consider any geodesic \( \gamma \subset F \) whose projection to each factor \( \mathbb{H} \) intersects the disc of radius \( r < \rho'' R' \) centered at the projection of \( p \) to that factor. Extend the geodesic so that its endpoints lie further than \( \epsilon R' \) from the disc. Choose a pair of points in \( F' \) within \( \epsilon R' \) of the endpoints of \( \gamma \) and let \( \gamma' \) be the geodesic in \( F' \) joining these points. Then \( \gamma' \) lies within Hausdorff distance \( \epsilon R' \) of \( \gamma \). Form the quadrilateral with two additional segments joining the endpoints of \( \gamma \) and \( \gamma' \). Since the endpoints are within \( \epsilon R' \) of each other, the segments joining the endpoints do not enter the disc of radius \( r \). The quadrilateral is \( 2\delta \)-thin, where \( \delta \) is the hyperbolicity constant for \( \mathbb{H} \). Therefore \( \gamma \) and \( \gamma' \) are within Hausdorff distance \( O(2\delta) \) of each other on the disc of radius \( r \).

**Proof of Theorem 4.1** By the second conclusion of Proposition 4.3 there exist \( \rho' \) and \( D_0 \) such that for all small \( \epsilon \) and large \( R \), for any \( x \in B_{\rho R}(z) \) and any flat \( F \)
through $x$, there is a flat $F'_x$ such that for $p \in F \cap B_{\rho' R}(x)$,
\[ d_H(\bar{f}(p), F'_x) \leq d(x, p) + D_0. \]
Now clearly, $d(\bar{f}(x), F'_x) \leq D_0$ for all $x$. By Lemma 4.4 there are $D = D(D_0, D'')$ and $\rho''$ such that for $\epsilon$ sufficiently small and $R$ large, and any pair of points
\[ x, p \in F \cap B_{\rho'' \rho' R}(z), \]
the flats $F'_p$ and $F'_x$, which correspond to $p$ and $x$ satisfying the above inequality, are within $D$ of each other. That is, given $F$ there is a single flat $F'$ such that for all $x$ in $F \cap B_{\rho'' \rho' R}(z)$,
\[ d_H(\bar{f}(x), F') \leq D. \]
Consider any geodesic $g_i$ in the $i$th factor of $\prod_{l=1}^{m} \mathbb{H}$ that intersects $B_{\rho'' \rho' R}(z_i)$ and fix the other coordinates so that we have a geodesic in $\prod_{l=1}^{m} \mathbb{H}$ that intersects $B_{\rho'' \rho' R}(z)$. Again denote it by $g_i$. Choose a pair of flats $F_1$ and $F_2$ that intersect exactly along $g_i$. Then, as we have seen, there are flats $F'_1$ and $F'_2$ such that for $j = 1, 2$,
\[ \bar{f}(F_j \cap B_{\rho'' \rho' R}(z_0)) \subset N_D(F'_j) \]
and thus, for both $j = 1, 2$,
\[ \bar{f}(g_i \cap B_{\rho'' \rho' R}(z_0)) \subset N_D(F'_j). \]
Since $\bar{f}$ is a quasi-isometric embedding the pair of flats $F'_1$ and $F'_2$ must come $O(D)$–close along a single geodesic of length comparable to $R$ in one factor in each. Thus we can assume that $\bar{f}$ factors along $g_i$ and sends its intersection with $B_{\rho'' \rho' R}(z_0)$ to within $O(D)$ of a geodesic $g'_j$ in a factor $j$.
Now let $\rho''' < 1$ and set $\rho = \rho''' \rho' \rho'$. Now consider any geodesic $g$ in the $i$th factor that intersects the smaller ball $B_{\rho R}(z_0)$. We have that $\bar{f}$ factors in the bigger ball $B_{\rho'' \rho' R}(z_0)$ along $g \cap B_{\rho'' \rho' R}(z_0)$. We claim that it also sends it to the same $j$th factor. Suppose not, so that it sends it to the $k \neq j$ factor. Choose a geodesic $\ell$ that comes close to both $g_i$ and $g$, possibly in the bigger ball $B_{\rho'' \rho' R}(z_0)$. Its image must change from the $j$th to the $k$th factor, which is impossible since the image of $\ell \cap B_{\rho'' \rho' R}(z_0)$ lies in a single factor up to bounded error. Thus the map is factor-preserving. □

5 Local factors in Teichmüller space

In this section we apply Theorem 4.1 to balls in Teichmüller space.
For a given $R > 0$ and $x \in \mathcal{T}$, define the $R$–decomposition at $x$ to be the decomposition $\mathcal{U}$ that contains a curve $\alpha$ if and only if $\tau_x(\alpha) \geq R$. That is, elements of $\mathcal{U}$ are either such curves or their complementary components. By convention, if $\mathcal{T} = \mathcal{T}(\Sigma, L)$ and $\Sigma$ has a component $U$ with $\xi(U) = 1$, then $U$ (not any annulus in $U$) is always included in any $R$–decomposition of $\Sigma$. This is because $\mathcal{T}(U)$ is already a copy of $\mathbb{H}$. An $R$–decomposition is maximal if there are no complementary components $W$ with $\bar{\tau}(W) > 1$. We always assume $f : \mathcal{T} \to \mathcal{T}$ is a $(K, C)$–quasi-isometry but, unless specified, it is not always assumed that $f$ is anchored.

**Proposition 5.1** For $K$ and $C$ as before, there are constants $0 < \rho_1 < 1$, $d_1$, $C_1$ and $D_1$ such that the following holds. For $x \in \mathcal{T}_{MR}$ let $R$ be such that

$$d(x, \mathcal{T}_{LR}) \geq R \geq d_1.$$  

Let $\mathcal{U}$ be the $R$–decomposition at $x$, let $\mathcal{V}$ be the $(R/2K)$–decomposition at $f(x)$ and let $r = \rho_1 R$. We have:

1. The decompositions $\mathcal{U}$ and $\mathcal{V}$ are maximal. For $x' \in B_r(x)$, we have $x' \in \mathcal{T}_\mathcal{U}$ and $f(x') \in \mathcal{T}_\mathcal{V}$.

2. There is a bijection $f_{x}^* : \mathcal{U} \to \mathcal{V}$ and, for every $U \in \mathcal{U}$ and $V = f_{x}^*(U)$, there is a $(K, C_1)$–quasi-isometry

$$\phi_{x}^U : B_r(xU) \to \mathcal{T}(V)$$

such that for all $x' \in B_r(x)$,

$$d_{\mathcal{T}(V)}(\phi_{x}^U(x'_U), f(x')_V) \leq D_1.$$  

**Remark 5.2** Property (2) above states that the map $f$ restricted to $B_r(x)$ is close to the product map $\prod_{U \in \mathcal{U}} \phi_{x}^U$. Note also that $\mathcal{U}$ depends on $R$, so $f_{x}^*$ too depends on $R$.

**Proof** Let $\alpha$ be the set of curves $\alpha$ with $\tau_x(\alpha) \geq R$. Since $d_{\mathcal{T}}(x, \mathcal{T}_{LR}) \geq R$ any complementary component $U$ of $\alpha$ must satisfy $\bar{\tau}(U) \leq 1$. Otherwise there would be a pair of adjacent curves $\gamma_1, \gamma_2 \subset U$ with $\tau_x(\gamma) < R$, which means that $d_{\mathcal{T}}(x, \mathcal{T}_{LR}) < R$. We conclude that $\mathcal{U}$ is a maximal decomposition.

Let $\rho_0 = 1/5K^2$. For $x' \in B_{\rho_0 R}(x)$, we have

$$\tau_{x'}(\alpha) \geq \tau_x(\alpha) - \rho_0 R \geq (1 - \rho_0) R.$$
This, if \( d_1 \) is large enough, implies that the curves \( \alpha \in \alpha \) are \( \ell_0 \)-short in \( x' \) and so \( x' \in T_\mathcal{U} \).

Let \( y \in T_{LR} \) be a point such that

\[
\Delta_T (f(x), y) = \Delta_T (f(x), T_{LR}).
\]

By Proposition 3.8,

\[
\Delta_T (f^{-1}(y), T_{LR}) \leq d_0.
\]

Using first the triangle inequality and then the fact that for some \( C' \), \( f^{-1} \) is a (coarse) \((K, C')\)-quasi-isometry, we get

\[
R = \Delta_T (x, T_{LR}) \leq \Delta_T (x, f^{-1}(y)) + d_0 \leq K \Delta_T (f(x), T_{LR}) + C' + d_0.
\]

By picking \( d_1 \) large enough in terms of \( d_0, K, C' \), we have

\[
(12) \quad \Delta_T (f(x), T_{LR}) \geq \frac{R}{2K}.
\]

Thus, as argued above, if \( \beta \) is the collection of curves \( \beta \) with \( \tau_{f(x)}(\beta) \geq R/2K \), then any complementary component \( V \) satisfies \( \xi(V) \leq 1 \). Hence, \( V \) is a maximal decomposition.

Again, since \( f \) is a \((K, C)\)-quasi-isometry, for all \( \beta \in \beta \) we have

\[
|\tau_{f(x)}(\beta) - \tau_{f(x')}(\beta)| \leq d(f(x), f(x')) \leq K d(x, x') + C
\]

\[
\leq K (\rho_0 R) + C \leq \frac{R}{5K} + C \leq \frac{R}{4K}.
\]

The last inequality holds for \( d_1 \) large enough. Thus, for \( x' \in B_{\rho_0 R}(x) \) and \( \beta \in \beta \),

\[
\tau_{f(x')}(\beta) \geq \tau_{f(x)}(\beta) - \frac{R}{4K} = \frac{R}{2K} - \frac{R}{4K}.
\]

Again, for \( d_1 \) large enough, this means \( \beta \) is \( \ell_0 \)-short and thus \( f(x') \in T_V \).

We have shown that \( x' \in B_{\rho_0 R}(x) \) implies \( x' \in T_\mathcal{U} \) and \( f(x') \in T_V \). By the Minsky product region theorem (Theorem 2.1) the maps \( \psi_\mathcal{U} \) and \( \psi_V \) are distance \( D_{pr} \) from an isometry. Define

\[
\widetilde{f}: \prod_{U \in \mathcal{U}} B_{\rho_0 R}(x_U) \to \prod_{V \in \mathcal{V}} T(V), \quad \widetilde{f} = \psi_V \circ f \circ \psi_\mathcal{U}^{-1}.
\]

Then, if we set \( C_1 = 2D_{pr} + C \), the map \( \widetilde{f} \) is a \((K, C_1)\)-quasi-isometry.

Because the map \( f \) has an inverse, \( \widetilde{f}(B_{\rho_0 R}(x)) \) contains a ball of comparable radius about \( \widetilde{f}(x) \). Now Theorem 4.1 applied to \( K = K \) and \( C = C_1 \) says that there
are constants $R_0$, $\rho$, $D$ and a bijection $f_x^* : \mathcal{U} \to \mathcal{V}$ such that for $r = \rho R$, the following holds. Assume $d_1 \geq R_0$. Then, for each $U \in \mathcal{U}$ and $V = f_x^*(U)$, there is a $(K, C_1)$–quasi-isometry
\[ \phi_x^U : B_r(x) \to \mathcal{T}(V) \]
such that for $x' \in B_r(x)$,
\[ d_{\mathcal{T}_V}(\tilde{f}(\psi_{xU}(x')), \prod_{U \in \mathcal{U}} \phi_x^U(x'_{xU})) \leq D. \]
The distance in $\mathcal{T}_V$ is the sup metric, each factor of which is either a copy of $\mathbb{H}$ or a horosphere $H_\beta \subset \mathbb{H}$. Hence, the inequality holds for every factor:
\[ d_{\mathcal{T}(V)}(\tilde{f}(\psi_{xU}(x'))_V, \phi_x^U(x'_{xU})) \leq D. \]
Therefore, for $\rho_1 = \rho R_0$, $D_1 = D$ and $d_1$ large enough, the proposition holds.

**Proposition 5.3** Choose $R$ so that
\[ r = \rho_1 R \geq \max(\rho_1 d_1, 4K(4D_1 + C_1)). \]
Let $x^1, x^2 \in \mathcal{T}$ be points such that
\[ d_{\mathcal{T}}(x^1, \mathcal{T}_{LR}) \geq R, \quad d_{\mathcal{T}}(x^2, \mathcal{T}_{LR}) \geq R, \quad d_{\mathcal{T}}(x^1, x^2) \leq r. \]
Assume every point $x \in B_r(x^1) \cup B_r(x^2)$ has the same $R$–decomposition $\mathcal{U}$ and the $(R/2K)$–decomposition at $f(x)$ always contains some subsurface $V$. Then, there is a $U \in \mathcal{U}$ such that
\[ f_{x^1}^*(U) = f_{x^2}^*(U) = V, \]
and, for every $u \in B_r(x^1) \cap B_r(x^2)$,
\[ d_{\mathcal{T}(V)}(\phi_{x^1}^U(u), \phi_{x^2}^U(u)) \leq 2D_1. \]

**Remark 5.4** Since $f_{x^i}^*$ is a bijection there must be some $U$ that is mapped to $V$. The content of the first conclusion is that the same $U$ works at both points.

**Proof** By assumption, for $x \in B_r(x^1) \cap B_r(x^2)$, the domain of $f_{x^i}^*$ is $\mathcal{U}$. We start by proving the following claim.

**Claim** For $z^1, z^2 \in B_r(x^1) \cap B_r(x^2)$ and $U \in \mathcal{U}$, suppose $f_{z^1}^*(U) = V$. Also, assume either
\[ d_{\mathcal{T}(U)}(z^1_U, z^2_U) \geq \frac{r}{4} \quad \text{and} \quad z^1_W = z^2_W \quad \text{for all} \ W \in \mathcal{U} \setminus \{U\} \]
or
\[ d_{T}(W)(z_{W}^{1}, z_{W}^{2}) \geq \frac{r}{4} \text{ for all } W \in \mathcal{U} - \{U\} \quad \text{and} \quad z_{U}^{1} = z_{U}^{2}. \]

That is, \( z^{1} \) and \( z^{2} \) either differ by \( \frac{r}{4} \) in only one factor, or all but one factor. Then \( f_{z_{2}}^{*}(U) = V \).

**Proof of claim** Assume the first case holds. Since \( \phi_{z_{1}}^{U} \) is a \((K, C_{1})\)–quasi-isometry (Proposition 5.1), we have
\[ d_{T}(\phi_{z_{1}}^{U}(z^{1}), \phi_{z_{1}}^{U}(z^{2})) \geq \frac{r}{4K} - C_{1}. \]

By Proposition 5.1 and the triangle inequality applied twice, we get
\[ d_{T}(f(z^{1})_{V}, f(z^{2})_{V}) \geq \frac{r}{4K} - C_{1} - 2D_{1}. \]

Now suppose \( f_{z_{2}}^{*}(W) = V \) for \( W \neq U \). Since \( z_{W}^{1} = z_{W}^{2} \), Proposition 5.1 and the triangle inequality then imply
\[ d_{T}(f(z^{1})_{V}, f(z^{2})_{V}) \leq 2D_{1}. \]

These two inequalities contradict the choice of \( R \) in the statement of the proposition, proving the claim. The proof of the claim under the second assumption is similar. \(<\)

We now prove the proposition. In each \( W \in \mathcal{U} \) choose \( z_{W} \) so that
\[ d_{T}(W)(z_{W}, x_{W}^{1}) = d_{T}(W)(z_{W}, x_{W}^{2}) = \frac{r}{4}. \]

Let \( z^{1}, z^{1,2} \) and \( z^{2} \) be points in \( B_{r}(x^{1}) \cap B_{r}(x^{2}) \) such that for \( i = 1, 2 \),
\[ z_{U}^{i} = z_{U} \quad \text{and} \quad z_{W}^{i} = x_{W}^{i} \quad \text{for all } W \in \mathcal{U} - \{U\}, \]

and such that
\[ z_{W}^{1,2} = z_{W} \quad \text{for all } W \in \mathcal{U}. \]

Note that the claim can be applied to pairs \((x^{1}, z^{1}), (z^{1}, z^{1,2}), (z^{1,2}, z^{2})\) and \((z^{2}, x^{2})\), concluding that
\[ V = f_{x_{1}}^{*}(U) = f_{z_{1}}^{*}(U) = f_{z_{1,2}}^{*}(U) = f_{z_{2}}^{*}(U) = f_{x_{2}}^{*}(U). \]

Now, consider \( u \in B_{r}(x_{U}^{1}) \cap B_{r}(x_{U}^{2}) \) and let \( z \in B_{r}(x^{1}) \cap B_{r}(x^{2}) \) be such that \( z_{U} = u \). We know
\[ d_{T}(V)(f(z)_{V}, \phi_{x_{1}}^{U}(u)) \leq D_{1} \quad \text{and} \quad d_{T}(V)(f(z)_{V}, \phi_{x_{2}}^{U}(u)) \leq D_{1}. \]
Therefore,

\[ d_{\mathcal{V}}(\phi_{x_1}^{U}(u), \phi_{x_2}^{U}(u)) \leq 2D_1. \]

This finishes the proof of the proposition. \( \square \)

**Corollary 5.5** If \( \mathcal{T} = \mathcal{T}(\Sigma, L) \) and \( U \) is a component of \( \Sigma \) with \( \xi(U) = 1 \), then for every \( x \in \mathcal{T}(\Sigma, L) \) where \( f_x^* \) is defined, \( f_x^*(U) = U \).

**Proof** Note that, by definition, the subsurface \( U \) is always included in any \( R \)–decomposition \( \mathcal{U} \) of \( \Sigma \). Hence, Proposition 5.3 applies. That is, for a large \( R \) as in Proposition 5.3, if \( f_x^*(U) = U \) then the same holds for points in an \( r \)–neighborhood of \( x \). But the set of points where \( f_x^* \) is defined is connected. Hence, it is enough to show \( f_x^*(U) = U \) for just one point \( x \).

Let \( \partial_L(U) \) be the projection of the boundary of \( \partial_L(\Sigma) \) to \( \mathcal{T}(U) \). Consider a geodesic \( g^U \) in \( \mathcal{T}(U) \) connecting a pair of points \( a \) and \( a' \) where

\[
\begin{align*}
  d_{\mathcal{T}(U)}(a, \partial_L(U)) &= d_{\mathcal{T}(U)}(a', \partial_L(U)) = R, \\
  d_{\mathcal{T}(U)}(g, \partial_L(U)) &\geq R, \quad d_{\mathcal{T}(U)}(a, a') \geq 4KR.
\end{align*}
\]

For example, we can choose a geodesic connecting two \( L \)–horoballs in \( \mathcal{T}(U) \) that otherwise stays in the thick part of \( \mathcal{T}(U) \) and then we can cut off a subsegment of length \( R \) from each end.

Let \( W = \Sigma - U \). Choose \( b \in \mathcal{T}(W) \) to have distance \( R \) from \( \partial_L(W) \) and let \( g \) be a path in \( \mathcal{T}(\Sigma, L) \) that has constant projection to \( W \) and projects to \( g^U \) in \( U \). That is,

\[
g(t)_W = b \quad \text{and} \quad g(t)_U = g^U(t).
\]

Then \( g \) connects a point \( x \in \mathcal{T}(\Sigma, L) \) to a point \( x' \in \mathcal{T}(\Sigma, L) \) where \( x_U = a, \ x'_U = a' \) and \( x_W = x'_W = b \).

Let \( y = f(x) \), \( y' = f(x') \) and let \( z \) and \( z' \) be points on \( \partial_L(\Sigma) \) that are distance \( R \) to \( x \) and \( x' \) respectively. Since \( f \) is anchored, we have

\[
d_{\mathcal{T}}(f(z), z) \leq C \quad \text{and} \quad d_{\mathcal{T}}(f(z'), z') \leq C,
\]

and hence

\[
d_{\mathcal{T}}(y, z) \leq d_{\mathcal{T}}(f(x), f(z)) + d_{\mathcal{T}}(f(z), z) \leq (KR + C) + C.
\]
The same holds for $d_T(y', z')$. Also,

$$d_{T(U)}(z_U, z'_U) \geq d_{T(U)}(x_U, x'_U) - d_T(z, x) - d_T(z', x') \geq d_{T(U)}(x_U, x'_U) - 2R.$$

Therefore,

$$d_{T(U)}(y_U, y'_U) \geq d_{T(U)}(z_U, z'_U) - d_{T(U)}(y_U, z_U) - d_{T(U)}(y'_U, z'_U) \geq d_{T(U)}(x_U, x'_U) - 2R - 2(KR + 2C) \geq \frac{1}{4} d_{T(U)}(x_U, x'_U).$$

The last inequality holds since $d_{T(U)}(x_U, x'_U) \geq 4KR$ and $2R + 2(KR + 2C) \leq 3KR$.

Now choose points

$$x = x_0, \ldots, x_N = x'$$

along $g$ so that $d_T(x_i, x_{i+1}) \leq r$ and

$$N = \frac{d_{T(U)}(x_U, x'_U)}{r} = \frac{d_{T(U)}(x_U, x'_U)}{\rho_1 R}.$$

As mentioned before, we already know $f_x^*(U) = f_{x_1}^*(U)$. If $f_x^*(U) \neq U$, then $f_{x_1}^*(U) \neq U$ and hence, by Proposition 5.1,

$$d_{T(U)}(f(x_i)U, f(x_{i+1}U)) \leq 2D_1.$$

Therefore,

$$d_{T(U)}(y_U, y'_U) \leq 2ND_1 \leq 2D_1 \frac{d_{T(U)}(x_U, x'_U)}{\rho_1 R}.$$

For $R$ large enough, this contradicts equation (13). Hence, $f_x^*(U) = U$. \hfill \Box

### 6 Nearly shortest curves

The goal of this section is to prove Proposition 6.9. Essentially, this states that if $\alpha$ is one of the shortest curves in $x$, then $\alpha$ is also short in $f(x)$ and, furthermore, $f_x^*(\alpha) = \alpha$.

Throughout this section we always assume, if $T = T(\Sigma, L)$, that $\Sigma$ does not have any components $U$ with $\chi(U) = 1$. Hence, Proposition 6.9 is the complementary statement to Corollary 5.5. The effect of this assumption is that every curve has an adjacent curve. The arguments are conceptually very elementary. However, we need to keep careful track of constants.
Cone is preserved

Recall that $S_x$ is the set of curves whose extremal length on $x$ is smaller than some fixed $\ell_0$. For $\eta > 1$, define the $\eta$–maximal cone $T_{MC}(\eta)$ to be the set of points $x \in T$ such that:

- $S_x$ is a pants decomposition, that is, $S_x = P_x$.
- For $\alpha, \beta \in P_x$, 
  \[
  \frac{\tau_x(\alpha)}{\tau_x(\beta)} \leq \eta. 
  \]

Let $\tau_x = \max_{\gamma \in P_x} \tau_x(\gamma)$. The value $\tau_x$ gives the maximum distance to travel to make the shortest curve have length $\ell_0$. To say $x$ lies in the cone says that the distance traveled to make any short curve have length $\ell_0$ are comparable up to factor $\eta$. For a point $z$ to be in $T_{LR}$, it has to contain two adjacent curves that have lengths larger than $\ell_0$. Hence, to reach lower rank costs at most $\tau_x$ and at least $\tau_x/\eta$. That is, for $x \in T_{MC}(\eta)$, we have

\[ \frac{\tau_x}{\eta} \leq d_T(x, T_{LR}) \leq \tau_x. \]

**Proposition 6.1** For every $\eta_0$, there is a $\tau_0$ such that if $x \in T_{MC}(\eta_0)$ and $\tau_x \geq \tau_0$, then

\[ f(x) \in T_{MC}(16K^2 \eta_0). \]

In fact, for every $\gamma \in P_{f(x)}$, we have

\[ \frac{\tau_x}{4K\eta_0} \leq \tau_{f(x)}(\gamma) \leq 4K\tau_x. \]

**Proof** Choose $R \geq d_1$ large enough so that if $d(x, T_{LR}) \geq R$ then, similarly to equation (12), we have

\[ \frac{d(x, T_{LR})}{2K} \leq d(f(x), T_{LR}) \leq 2Kd(x, T_{LR}), \]

and so that

\[ r = \rho_1 R \geq 32K \eta_0 D_1. \]

Let $\tau_0 = 16K^2 \eta_0 R$.

**Claim** For adjacent curves $\beta, \beta' \in P_{f(x)}$ we have

\[ \tau_{f(x)}(\beta) \leq \frac{\tau_x}{4K\eta_0} \Rightarrow \tau_{f(x)}(\beta') \geq 4K\tau_x. \]
We will later prove that in fact $\tau_{f(x)}(\beta') < 4K\tau_x$. Assiming this inequality and the claim we can finish the proof of the proposition. Indeed the claim says that for $\beta$ adjacent to $\beta'$, one has $\tau_x/(4K\eta_0) \leq \tau_{f(x)}(\beta)$.

**Proof of claim** We prove the claim by contradiction. Assume that the first inequality in the claim holds and the second is false. Note that we still have, by equations (13) and (14), that

$$\max(\tau_{f(x)}(\beta'), \tau_{f(x)}(\beta)) \geq d_T(f(x), TLR) \geq \frac{d_T(x, TLR)}{2K} \geq \frac{\tau_x}{2\eta_0 K}.$$ 

To summarize, we have two adjacent curves $\beta$ and $\beta'$ with

$$\tau_{f(x)}(\beta) \leq \frac{\tau_x}{4K\eta_0} \quad \text{and} \quad \frac{\tau_x}{2K\eta_0} \leq \tau_{f(x)}(\beta') \leq 4K\tau_x.$$ 

Consider a geodesic $g$ moving only in the $\beta'$ factor that increases the length of $\beta'$ and connects $f(x)$ to a point $f(x')$ with

$$\tau_{f(x')}(\beta') = \frac{\tau_x}{4K\eta_0} \geq \frac{\tau_0}{4K\eta_0} \geq R.$$ 

We have

(16) $$d(f(x'), TLR) \leq \frac{\tau_x}{4K\eta_0}.$$ 

Take a sequence of points

$$f(x) = y_1, y_2, \ldots, y_N = f(x')$$

along $g$ with $d_T(y_i, y_{i+1}) \leq r$ and

$$N = \frac{4K\tau_x}{r}.$$ 

Let $h = f^{-1}$, let $x_i = h(y_i)$, let $V_i$ be the $R$–decomposition at $y_i$ and $U_i$ be the $(R/2K)$–decomposition at $x_i$. By assumption, $\tau_{y_i}(\beta') \geq R$ and hence $\beta' \in V_i$ for every $i$ and, since the length of no other curve is changing along $g$, all $V_i$ are in fact the same decomposition (which we denote by $V$). Also $U_1 = P_x$. Let $\alpha' = h_{y_1}^*(\beta')$.

Let $\alpha \in P_x$ with $\alpha \neq \alpha'$. Let $V \in V$ be the component such that $h_{y_1}^*(V) = \alpha$. We show by induction on $i$ that $\alpha \in U_i$ and $h_{y_i}^*(V) = \alpha$. Assume this for $1 \leq i < j$. Since $y_{i+1} \in B_r(y_i)$, and $y_i$ and $y_{i+1}$ have the same projection to $T(V)$, Proposition 5.1 implies

$$d_T(\alpha, x_i^\alpha, x_{i+1}^\alpha) \leq 2D_1.$$

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Therefore,
\[
d_{\mathcal{T}(\alpha)}(x^{1}_\alpha, x^{j}_\alpha) \leq 2jD_1 \leq 2N D_1 \leq \frac{8K \tau_x}{r} D_1 \leq \frac{\tau_x}{4\eta_0}.
\]

The last inequality is from the assumption on \(r\). Hence,
\[
\tau_{x^j}(\alpha) \geq \frac{\tau_x}{\eta_0} - \frac{\tau_x}{4\eta_0} \geq \frac{3\tau_x}{4\eta_0}.
\]

This means in particular that \(\alpha\) is short enough \((\tau_{x^j}(\alpha) \geq R/2K)\) and is included in \(\mathcal{U}_j\). Moreover, by Proposition 5.3, \(h^*_{y_j}(V) = \alpha\), completing the induction step. Continuing this way, we conclude that, for every \(\alpha \in \mathcal{P}_x\), \(\alpha \neq \alpha'\), we have
\[
\tau_{x'}(\alpha) \geq \frac{3\tau_x}{4\eta_0}.
\]

In particular, the above inequality holds for every pair of adjacent curves in \(x'\). But
\[
d_{\mathcal{T}}(x', \mathcal{T}_{LR}) \leq 2Kd_{\mathcal{T}}(f(x'), \mathcal{T}_{LR}) \leq \frac{\tau_x}{2\eta_0}.
\]

This is a contradiction, which proves the claim. \(\square\)

We now show that all curves \(\beta \in P_{f(x)}\) must in fact satisfy
\[
\tau_{f(x)}(\beta) < 4K \tau_x.
\]

The argument is similar to the one above, so we skip some of the details. Suppose this is false for some curve \(\beta\). Let \(\alpha\) be a curve such that \(f^*_x(\alpha) = \beta\), and \(\alpha'\) be a curve adjacent to \(\alpha\). Let \(g\) be a geodesic that moves only in the \(\alpha\) and \(\alpha'\) factors, increasing their lengths, and that connects \(x\) to a point \(x'\) where
\[
\tau_x(\alpha) = \tau_x(\alpha') = R.
\]

We find a collection of points
\[
x = x_1, \ldots, x_N = x'
\]
on \(g\) such that \(d(x, x') \leq r\) and \(N = \tau_x/r\). Let \(\mathcal{U}_i\) be the \(R\)-decomposition at \(x_i\) and \(\mathcal{V}_i\) be the \((R/2K)\)-decomposition at \(y_i = f(x_i)\). Then, as before, \(\alpha\) and \(\alpha'\) are in every \(\mathcal{U}_i\) (in fact, all \(\mathcal{U}_i\) are the same decompositions which we denote by \(\mathcal{U}\)). Let \(f^*_x(\alpha') = V'\). By an argument as above, the total movement in any other factor (besides \(\beta\) and \(V'\)) is at most \(2N D_1\).
Since \( d_\mathcal{T}(x_N, T_{LR}) = R \), we have \( d_\mathcal{T}(y_N, T_{LR}) \leq 2KR \). That is, there are two adjacent curves \( \gamma \) and \( \gamma' \) with

\[
\tau_{y_N}(\gamma), \tau_{y_N}(\gamma') \leq 2KR.
\]

But, for \( R \) large enough, we have

\[
\tau_{y_N}(\beta) \geq \tau_{y_1}(\beta) - N(Kr + C) \geq 4K\tau_x - \frac{\tau_x}{r}(Kr - C) \geq \frac{5}{2}K\tau_x.
\]

Hence, neither \( \gamma \) nor \( \gamma' \) equals \( \beta \). And one, say \( \gamma' \), is not contained in \( V' \). Therefore,

\[
\tau_{y_1}(\gamma') \leq \tau_{y_N}(\gamma') + 2ND_1 \leq 2KR + 2\frac{\tau_x}{r}D_1
\]

\[
\leq \frac{2KR}{\tau_0} + \frac{2D_1}{r} < \left( \frac{1}{8K\eta_0} + \frac{1}{16K\eta_0} \right)\tau_x < \frac{\tau_x}{4K\eta_0}.
\]

Now, \( \gamma \) is adjacent to \( \gamma' \), so \( \tau_{y_1}(\gamma) \geq 4K\tau_x \) by the claim. However, again as above,

\[
\tau_{y_N}(\gamma') \geq \tau_{y_1}(\gamma') - N(Kr + C) \geq 4K\tau_x - \frac{\tau_x}{r}(Kr + C) \geq \frac{5}{2}K\tau_x.
\]

This contradicts equation (17). We are done.

\[\square\]

**Induced map on the curve complex is cellular**

Let \( \mathcal{P}(S) \) be the complex of pants decompositions of \( S \). For a pants decomposition \( P \in \mathcal{P}(S) \), define \( T_{MC}(P, \eta_0) \) to be the set of points \( x \in T_{MC}(\eta_0) \) where \( P_x = P \). Note that \( T_{MC}(\eta_0) \) is not connected and its connected components are parametrized by \( \mathcal{P}(S) \):

\[
T_{MC}(\eta_0) = \bigcup_{P \in \mathcal{P}(S)} T_{MC}(P, \eta_0).
\]

The same is true for \( T_{MC}(16K^2\eta_0) \) and, by Proposition 6.1,

\[
f(T_{MC}(\eta_0)) \subset T_{MC}(16K^2\eta_0).
\]

Hence, we can define a bijection \( f^*_P : \mathcal{P}(S) \to \mathcal{P}(S) \) so that

\[
f(T_{MC}(P, \eta_0)) \subset T_{MC}(f^*_P(P), 16K^2\eta_0).
\]

We will show that \( f^*_P \) is induced by a simplicial automorphism \( f^*_C \) of the curve complex. Note that the definition of \( f^*_P \) depends on the choice of \( \eta_0 \).
Proposition 6.2  Assuming $\eta_0$ is large enough, there exists a simplicial automorphism $f_\mathcal{C}^*: \mathcal{C}(S) \rightarrow \mathcal{C}(S)$ such that, for a pants decomposition $P = \{\alpha_1, \ldots, \alpha_n\}$, we have

$$f_\mathcal{P}^*(P) = \{f_\mathcal{C}^*(\alpha_1), \ldots, f_\mathcal{C}^*(\alpha_n)\}.$$  

Proof  Recall we have constants $d_1$ and $\rho_1$ from Proposition 5.1. Choose $R, \eta_0$ and $d$ so that

$$\eta_0 d \geq R \geq d_1 \quad \text{and} \quad r = \rho_1 R \geq 2d.$$ 

Let $\alpha$ be a multicurve containing $\xi(S) - 1$ curves and let

$$P = \alpha \cup \{\beta\} \quad \text{and} \quad P' = \alpha \cup \{\beta'\}$$

be two extensions of $\alpha$ to pants decompositions with $i(\beta, \beta') \leq 2$. Let $x$ be a point in $\mathcal{T}_{\mathcal{MC}}(P, \eta_0)$ such that $\tau_x(\beta) = d$ and $\tau_x(\alpha) = \eta_0 d$ for $\alpha \in \alpha$. Similarly, define $x' \in \mathcal{T}_{\mathcal{MC}}(P', \eta_0)$ so that

$$x'_\alpha = x_\alpha \quad \text{for all} \quad \alpha \in \alpha, \quad \tau_{x'}(\beta') = d \quad \text{and} \quad d_T(x, x') \leq 2d.$$ 

Let $\mathcal{U}$ be the decomposition consisting of $\alpha$ and the complementary subsurface $U$. Then $x, x' \in T_\mathcal{U}$. Let $g$ be a path connecting $x$ to $x'$ whose projection is constant in every $T(\alpha)$ for $\alpha \in \alpha$, is a geodesic connecting $x_U$ to $x'_U$ in $T(U)$, and has length $2d$. We have

$$d_T(g, T_{LR}) \geq \eta_0 d \geq R.$$ 

Hence, Propositions 5.1 and 5.3 apply to $x$ and $x'$. This means $f(x)$ and $f(x')$ are contained in the same product region, say $T_V$. Let $V = f_X^*(U)$. Then, for $W \in \mathcal{V}$ with $W \neq V$,

$$d_T(W)(f(x)_W, f(x')_W) \leq 2D_1.$$ 

But

$$f(x) \in \mathcal{T}_{\mathcal{MC}}(f_\mathcal{P}^*(P), 16K^2\eta_0) \quad \text{and} \quad f(x') \in \mathcal{T}_{\mathcal{MC}}(f_\mathcal{P}^*(P'), 16K^2\eta_0).$$ 

Hence, $\mathcal{V}$ contains a multicurve $\gamma$ with $\xi(S) - 1$ curves, and $f_\mathcal{P}^*(P)$ and $f_\mathcal{P}^*(P')$ share all but one curve. That is, there are curves $\delta$ and $\delta'$ such that

$$f_\mathcal{P}^*(P) = \gamma \cup \{\delta\} \quad \text{and} \quad f_\mathcal{P}^*(P') = \gamma \cup \{\delta'\}.$$ 

However, for the moment, we do not have a good bound on the intersection number $i(\delta, \delta')$.

We first show that the multicurve $\gamma$ does not depend on the choice of $\beta'$. Assume $\beta''$ is another curve with $i(\beta, \beta'') \leq 2$, and let $P'' = \alpha \cup \{\beta''\}$. If $i(\beta, \beta'') \leq 2$ then...
$f^*_P(P)$, $f^*_P(P')$ and $f^*_P(P'')$ share $\xi(S) - 1$ curves. Hence, these have to be the same multicurve $\gamma$. If $i(\beta', \beta'')$ is large, then we can find a sequence

$$\beta' = \beta_1, \ldots, \beta_m = \beta''$$

deviation. Let

Similarly, $\gamma$ cannot contain both $P$ and $Q$. Since $P \in \mathcal{P}$, we know that there are curves $D$. That is, the same curve changes from $f^*_P(P)$ to $f^*_P(P'')$ as it did from $f^*_P(P)$ to $f^*_P(P')$ and $\gamma \subset f^*_P(P'')$.

Note that we have shown that there is an association between curves in $P$ and $f^*_P(P)$. Namely let $\beta \in P$ and $\alpha$ be the set of complementary $\xi - 1$ curves in $P$. Let $P'$ any pants decomposition that contains $\alpha$ but not $\beta$. Then $\beta \in P$ is associated to the curve $P(\beta) \in f^*_P(P)$ that is not contained in $f^*_P(P')$. We will show $P(\beta)$ is the same for every $P$; that is, it does not depend on $\alpha$.

Let $\alpha$ be a multicurve with $\xi(S) - 2$ curves and let $P = \alpha \cup \{\beta_1, \beta_2\}$ be a pants decomposition. Let

$$P_1 = \alpha \cup \{\beta'_1, \beta_2\}, \quad P_2 = \alpha \cup \{\beta_1, \beta'_2\}, \quad P_{12} = \alpha \cup \{\beta_1', \beta_2'\},$$

with $i(\beta_i, \beta'_i) \leq 2$ for $i = 1, 2$. Denote

$$Q = f^*_P(P), \quad Q_1 = f^*_P(P_1), \quad Q_2 = f^*_P(P_2), \quad Q_{12} = f^*_P(P_{12}).$$

Let $\gamma$ be a multicurve with $\xi(S) - 2$ curves such that $Q = \gamma \cup \{P(\beta_1), P(\beta_2)\}$. From the discussion above, we know that there are curves $\delta_1$ and $\delta_2$ such that

$$Q_1 = \gamma \cup \{\delta_1, P(\beta_2)\} \quad \text{and} \quad Q_2 = \gamma \cup \{P(\beta_1), \delta_2\}.$$  

Since $P(\beta_1)$ and $P(\beta_2)$ are disjoint, the curves $\delta_1$ and $\delta_2$ must be different. Also $Q_{12}$ shares $\xi(S) - 1$ curves with both $Q_1$ and $Q_2$. But the map $f^*_P$ is a bijection and $Q_{12} \neq Q$. Moreover, since $\delta_1 \neq \delta_2$ and $P(\beta_1)$ and $P(\beta_2)$ are disjoint, $Q_{12}$ cannot contain both $P(\beta_1)$ and $\delta_1$ and similarly it cannot contain both $P(\beta_2)$ and $\delta_2$. Therefore,

$$Q_{12} = \gamma \cup \{\delta_1, \delta_2\}.$$  

That means $P_2(\beta_1) = P(\beta_1)$ because it is the curve that changes from $Q_2$ to $Q_{12}$. Similarly, $P_1(\beta_2) = P(\beta_2)$.

W have shown the association $\beta \rightarrow P(\beta)$ is the same for adjacent pants decompositions in $\mathcal{P}(S)$. Hence, it does not depend on $P$ and we can define $f^*_C(\beta) = P(\beta)$ for any pants decomposition $P$ containing $\beta$.
Every multicurve is contained in a pants decomposition. Hence \( f^*_C \) sends disjoint curves to disjoint curves and in fact sends simplices in \( \mathcal{C}(S) \) to simplices. Since \( f^*_P \) is onto, \( f^*_C \) is also onto. We show \( f^*_C \) is one-to-one. Assume for the sake of contradiction that \( f^*_C(\alpha) = f^*_C(\beta) \), and let \( P_\alpha \) and \( P_\beta \) be pants decompositions that contain \( \alpha \) and \( \beta \), respectively, but have no curves in common. Then \( f^*_P(P_\alpha) \) and \( f^*_P(P_\beta) \) share a curve \( \delta \). Let

\[
f^*_P(P_\alpha) = Q_1, \ldots, Q_m = f^*_P(P_\beta)
\]

be a sequence of adjacent pants decompositions all containing \( \delta \) and let \( P_i = f^*_P^{-1}(Q_i) \). Then \( f^*_C^{-1}(\delta) \) is contained in every \( P_i \). This contradicts the assumption that \( P_\alpha \) and \( P_\beta \) have no common curves.

We have shown \( f^*_C \) is simplicial and it is a bijection; that is, it is a simplicial automorphism of \( \mathcal{C}(S) \).

**Remark 6.3** In the case \( \mathcal{T} = \mathcal{T}(S) \), by a theorem of Ivanov [15], \( f^*_C \) is induced by an isometry \( f^* \) of Teichmüller space \( \mathcal{T}(S) \). Hence, after applying the inverse of this isometry to \( f \), we can assume that \( f^*_C \) is the identity map. In the case that \( \mathcal{T} = \mathcal{T}(\Sigma, L) \) and \( f \) is anchored, we know that \( f^*_P \) is the identity map. Thus, so is \( f^*_C \). Indeed, for the remainder of the paper, we assume that in these cases \( f^*_C \) is the identity.

**Remark 6.4** We point out that \( f^*_C \) and \( f^*_x \) are different maps. We now show that on each \( \eta_0 \) cone the latter map is the identity as well.

**Corollary 6.5** Assume either \( f = f_S \) or \( f = f_{\Sigma} \) is anchored. Let \( x \in \mathcal{T}_{MC}(P, \eta_0) \) be a point with

\[
\tau_x \geq \max(\tau_0, 8\eta_0^2 d_1).
\]

Then, for \( \alpha \in P \), we have \( f^*_x(\alpha) = \alpha \).

**Proof** Let \( R = \tau_x/2\eta_0 \). Then the \( R \)-decomposition at \( x \) is \( P_x \) and the \( (R/2K) \)-decomposition of \( f(x) \) is also \( P_x \). This is because, by Remark 6.3 and Proposition 6.1 we have, for \( \alpha \in P_x \),

\[
\tau_{f(x)}(\alpha) \geq \frac{\tau_x}{4K\eta_0} = \frac{R}{2K}.
\]

Hence, \( f^*_x(\alpha) \) is some curve in \( P_x \).
Take $\gamma \in P$, $\gamma \neq \alpha$, and let $\gamma'$ be a curve intersecting $\gamma$ once or twice and that is disjoint from other curves in $P$, and let

$$P' = (P - \{\gamma\}) \cup \{\gamma'\}.$$ 

Let $x' \in \mathcal{T}_{MC}(P', \eta_0)$ be a point such that $x_\beta = x'_\beta$ for all $\beta \in P - \{\gamma\}$ and $\tau_x(\gamma) = \tau_{x'}(\gamma')$.

Let $g$ be a path connecting $x$ to $x'$ that is constant in all other factors. The length of $\gamma$ changes by at least $2\tau_x(\gamma)/\eta_0$. As argued before, since $\alpha$ remains short along $g$, the length of $f_x^*(\alpha)$ changes by at most $2N\log 1/R$ where $N = \tau_x/\rho_1 R$. The choice of $\tau_x$ says this is less than the change in the length of $\gamma$. Hence, $f_x^*(\alpha) \neq \gamma$. Since we can use this argument for every curve $\gamma \neq \alpha$, we conclude $f_x^*(\alpha) = \alpha$. □

The restriction to the thick part

**Proposition 6.6** Assume $f_P^*$ is the identity. Then there is constant $D_{\text{thick}}$ such that if $x$ is $\ell_0$–thick, then

$$d_T(f(x), x) \leq D_{\text{thick}}.$$

**Proof** Let $B > 0$ be the Bers constant, which has the property that the set of curves of length at most $B$ fill $x$. To find an upper-bound for $d(x, f(x))$ it is enough to show that $\alpha$ has bounded length in $f(x)$ for each $\alpha$ with $\text{Ext}_x(\alpha) \leq B$. (This follows, for example, from [5, Theorem B] and the fact that extremal length and hyperbolic lengths are comparable in a thick surface $x$.)

Let $\eta_0$ be as in Proposition 6.2 and $\tau_0$ be as in Proposition 6.1. For $\alpha$ as above, let $P$ be a pants decomposition containing $\alpha$, and $z \in \mathcal{T}_{MC}(P, \eta_0)$ be such that $\tau_z = \tau_0$ and $d_T(x, z) = \frac{\tau_0}{\log \text{Ext}_z(\alpha)}$. Then, by Proposition 6.1,

$$\tau_f(z)(\alpha) \geq \frac{\tau_0}{4K\eta_0}.$$

Now we have

$$K\tau_0 \geq d_T(f(x), f(z)) \geq \log \frac{\text{Ext}_{f(x)}(\alpha)}{\text{Ext}_{f(z)}(\alpha)} \geq \log \text{Ext}_{f(x)}(\alpha).$$

Hence,

$$\log \text{Ext}_{f(x)}(\alpha) \geq K\tau_0.$$

That is, the length of all such $\alpha$ in $f(x)$ is uniformly bounded and hence $d_T(x, f(x))$ is uniformly bounded as well. □
Grouping of sizes

**Definition 6.7** Fix once and for all

\[ \mu = 64K^4D_1^2. \]

Suppose we have a set \( \{d_1, d_2, \ldots, d_m\} \) of positive numbers. We say that \( \eta \) is an admissible scale for this set if there is a decomposition \( \mathcal{E} \) of this set such that, if \( d_i, d_j \in E \) for \( E \in \mathcal{E} \), then \( d_j/d_i \leq \eta \), and if they are in different subsets, then \( \max(d_i/d_j, d_j/d_i) \geq \mu \eta \). We refer to \( \mathcal{E} \) as the partition associated to \( \eta \). We call the set \( E \in \mathcal{E} \) containing the largest elements the top group.

**Lemma 6.8** Given \( \eta_0 > 1 \), there are scales \( \eta_0 < \eta_1 < \cdots < \eta_m \) such that for any set \( \{d_1, d_2, \ldots, d_m\} \) of positive numbers, some \( \eta_i \) is an admissible scale for this set. In fact, we can define \( \eta_i \) recursively as

\[ \eta_{i+1} = \mu \eta_i^3. \]

**Proof** For \( 1 \leq i \leq m \), let \( \mathcal{E}_i \) be the partition of \( \{d_1, d_2, \ldots, d_m\} \) containing the smallest number of subsets such that, for \( E \in \mathcal{E}_i \) and \( d, d' \in E \), we have \( d/d' \leq \eta_i \). If we also have \( d/d' \geq \mu \eta_i \) for \( d \geq d' \) in different sets, then \( \eta_i \) is an admissible scale and we are done. Otherwise, for every \( i \), there are two distinct sets \( E, E' \in \mathcal{E}_i \), with \( d \in E \) and \( d' \in E' \), where \( d \geq d' \) and \( d/d' \leq \eta_i \mu \). Then, for any \( c \in E \) and \( c' \in E' \) we have

\[ \frac{c}{c'} \leq \frac{d}{d'} \cdot \frac{d'}{c'} \leq \mu \eta_i^3 = \eta_{i+1}. \]

This means \( E \) and \( E' \) fit in one group in \( \mathcal{E}_{i+1} \) and

\[ |\mathcal{E}_{i+1}| = |\mathcal{E}_i| - 1. \]

If this holds for all \( i \), then some \( \mathcal{E}_j \) has size 1 and \( \eta_j \) would be an admissible scale. \( \square \)

**The shortest curves are preserved**

**Proposition 6.9** Assume either \( f = f_S \) or \( f = f_\Sigma \) is anchored. For \( \tau_1 \) large enough, the following holds. Let \( x \in T \) be a point such that \( \tau_x(\alpha) \geq \tau_1 \) for \( \alpha \in P_x \), and let \( \eta \) be an admissible scale for the set \( \{\tau_x(\alpha)\}_{\alpha \in P_x} \) with the associated partition \( \mathcal{E} \). Let \( E \) be the top group in \( \mathcal{E} \) and let \( \alpha \) be the set of curves \( \alpha \) where \( \tau_x(\alpha) \in E \). Then, for every \( \alpha \in \alpha \), we have

\[ \frac{\tau_x}{\sqrt{\mu \eta}} \leq \tau_{f(x)}(\alpha) \leq 2K\tau_x, \]

and \( f_x^*(\alpha) = \alpha \).
Proof For $\tau_1$ large enough,
\[ \tau_{f(x)}(\alpha) \leq d_{\mathcal{T}}(f(x), T_{\text{thick}}) \leq Kd_{\mathcal{T}}(x, T_{\text{thick}}) + C + D_{\text{thick}} \leq K\tau_x + C + D_{\text{thick}} \leq 2K\tau_x. \]
Hence, we have the upper-bound. We also require that
\[ \tau_1 > \frac{128D_1^2K\eta m}{\rho_1}, \]
where $\eta m \geq \eta$ is from Lemma 6.8. Let $r = \rho_1 \tau_1$ and let $y = f(x)$. Let $\beta$ be the set of curves $\beta$ with $\tau_y(\beta) \geq \tau_x/\sqrt{\mu}\eta$.

Claim $|\beta| \leq |\alpha|$.

Proof of claim The proof is essentially the same as the proof of Proposition 6.1. Choose a path $g$ that changes the lengths of curves in $\alpha$ only connecting $x$ to a point $x'$ such that $\tau_{x'}(\alpha) = \tau_x/\eta\mu$ for $\alpha \in \alpha$, and $d_{\mathcal{T}}(x, x') \leq \tau_x$. Since all other curves in $x$ are already shorter that $\tau_x/\eta\mu$, we have
\[ \tau_{x'} = \frac{\tau_x}{\eta\mu}. \]
We can cover $g$ with points
\[ x = x_1, \ldots, x_N = x' \]
such that $d_{\mathcal{T}}(x_i, x_{i+1}) \leq r$ and $N = \tau_x/r$. Let $k = |\alpha|$ and $y' = f(x')$. Then, as in the proof of Proposition 6.1, only the lengths of $k$ curves can change substantially from $y$ to $y'$. More precisely, if $\beta$ has more than $k$ curves, then there is a $\beta \in \beta$ such that
\[ |\tau_y(\beta) - \tau_{y'}(\beta)| \leq 2ND_1. \]
Also, $\tau_{y'} \leq 2K\tau_{x'} = 2K\tau_x/\eta\mu$. Hence,
\[ \tau_y(\beta) \leq \tau_{y'}(\beta) + 2ND_1 \leq \frac{2K\tau_x}{\eta\mu} + \frac{2D_1\tau_x}{r} \leq \frac{\tau_x}{3\eta\sqrt{\mu}}. \]
The last inequality comes from our choice of $\mu$, $\tau_1$ and the fact that $r = \rho_1 \tau_1$. We have a contradiction to the assumption $\beta \in \beta$. This proves the claim.

We now show that, in fact, $\alpha = \beta$. Assume there is a curve $\alpha \in \alpha - \beta$. Let $w$ be a point such that
\[ w_\beta = y_\beta \quad \text{for all } \beta \in \beta, \quad \tau_w(\beta) = 0 \quad \text{for all } \beta \in P_y - \beta, \quad d_{\mathcal{T}}(y, w) \leq \frac{\tau_x}{\sqrt{\mu}\eta}. \]
Let $P$ be a pants decomposition containing $\beta$ such that
\[ i(P, \alpha) \neq 0 \quad \text{and} \quad \text{Ext}_w(\beta') \leq B \quad \text{for all } \beta' \in P - \beta. \]
Let \( y' \in \mathcal{T}_{MC}(P, \sqrt{\mu} \eta) \) be a point obtained from \( w \) by pinching curves \( \beta' \in P - \beta \) until \( \tau_{y'}(\beta') = \tau_y/\sqrt{\mu} \eta \). Then
\[
d_{\mathcal{T}}(w, y') \leq \frac{\tau_y}{\sqrt{\mu} \eta} + d_{\text{pinch}} \leq \frac{(2K + 1)\tau_x}{\sqrt{\mu} \eta} \quad \text{and hence} \quad d_{\mathcal{T}}(y, y') \leq \frac{(2K + 2)\tau_x}{\sqrt{\mu} \eta}.
\]

By Proposition 6.1, all curves in \( P \) are still short in \( x' = f^{-1}(y') \). This means \( \alpha \) is not short, and hence
\[
d_{\mathcal{T}}(x, x') \geq \tau_x(\alpha) \geq \frac{\tau_x}{\eta}.
\]
But we also have
\[
d_{\mathcal{T}}(x, x') \leq Kd_{\mathcal{T}}(y, y') + C \leq \frac{(2K^2 + 2K)}{\sqrt{\mu} \eta} \tau_x + C.
\]

The choice of \( \mu \) gives a contradiction between the last two inequalities. This proves \( \alpha \subset \beta \). This and the claim imply \( \alpha = \beta \).

We now show \( f^*_x(\alpha) = \alpha \) for \( \alpha \in \alpha \). This essentially follows from Corollary 6.5. Let \( g \) be a path connecting \( x \) to a point \( x' \in \mathcal{T}_{MC}(P_x, \eta_0) \) that is constant in the \( \alpha \) coordinate (that is, changes the length of all curves until they are comparable to \( \alpha \)). Note that \( \tau_{x'} \) is large enough that Corollary 6.5 applies. But, by Corollary 6.5, \( f^*_x(\alpha) = \alpha \). And, as we have argued in the proof of claim in Proposition 6.1, as we move along \( g \) from \( x' \) to \( x \), the curve \( \alpha \) remains short both in \( g(t) \) and \( f(g(t)) \). Hence, Proposition 5.3 applies to all points along this path and \( f^*_x(\alpha) = \alpha \) as well. We are done.

\section{Applying induction}

We start by proving the base case of induction (Theorem 1.2). Note that when \( \xi(\Sigma) = 1 \), the surface \( \Sigma \) is connected and is either a punctured torus or a four-times-punctured sphere and \( \mathcal{T}(\Sigma) = \mathbb{H} \).

\textbf{Proposition 7.1} Assume \( \xi(\Sigma) = 1 \) and \( K_{\Sigma} \) and \( C_{\Sigma} \) are given. Then Theorem 1.2 holds for \( L_{\Sigma} = 0 \) and some constant \( D_{\Sigma} \).

\textbf{Proof} Let \( L \geq L_{\Sigma} = 0 \) be given. Consider a point \( z \in \mathcal{T}(\Sigma, L) \). For \( i = 1, 2 \), let \( g_i: [a_i, b_i] \to \mathcal{T}(\Sigma, L) \) be a geodesic such that \( g_i(0) = z \) and \( g_i(a_i) \) and \( g_i(b_i) \) lie on distinct \( L \)–horocycles, and such that \( g_1 \) and \( g_2 \) have a definite angle between them; see Figure 2. Define \( \bar{g}_i = f_{S} \circ g_i \). Then \( \bar{g}_i \) is a \( (K_{\Sigma}, C_{\Sigma}) \)–quasigeodesic. Since \( f_{S} \) is anchored, the endpoints of \( \bar{g}_i \) are uniformly bounded distance from the endpoints of \( g_i \). This implies \( \bar{g}_i \) is contained in a uniformly bounded neighborhood of \( g_i \). This
means $f(z) = \bar{g}_i(0)$ is contained in a uniformly bounded neighborhood of both $g_1$ and $g_2$. But, since $g_1$ and $g_2$ have a definite size angle between them, the diameter of this set is uniformly bounded. Hence, $d_{\mathbb{H}}(z, f(z))$ is uniformly bounded. 

Our plan is to apply induction by removing from $\Sigma$ all components of complexity 1 and by cutting along the shortest curves.

**Proposition 7.2** Assume that $\Sigma$ has a component $W$ with $\xi(W) = 1$. Suppose that $f: \mathcal{T}(\Sigma, L) \to \mathcal{T}(\Sigma, L)$ is a $(K, C)$–quasi-isometry that is $C$–anchored. Pick a large $R$ so that the statements in Section 5 apply. Then, there is a constant $D_W$ such that the following holds. Let $z \in \mathcal{T} = \mathcal{T}(\Sigma, L)$ be a point such that

$$d_{\mathcal{T}}(z, \partial L(\Sigma)) \geq R.$$ 

Then

$$d_{\mathcal{T}(W)}(z_W, f(z)_W) \leq D_W.$$  

**Proof** Let $\Sigma' = \Sigma - W$. We denote a point $x \in \mathcal{T}(\Sigma)$ as a tuple $(x_W, x_{\Sigma'})$. Let $r = \rho_1 R$.

**Claim 1** Let $g: [a, b] \to \mathcal{T}(W)$ be a geodesic that stays a distance at least $R$ from $\partial L(W)$ and let

$$x_t = (g(t), \Sigma') \in \mathcal{T}(\Sigma, L).$$

Define

$$\bar{g}(t) = f(x_t)_W.$$ 

Then $\bar{g}$ is a quasigeodesic.

**Proof of Claim 1** To see the upper bound, we note that, for times $s$ and $t$,

$$d_{\mathcal{T}(W)}(\bar{g}(t), \bar{g}(s)) = d_{\mathcal{T}(W)}(f(x_t)_W, f(x_s)_W) \leq d_{\mathcal{T}(\Sigma)}(f(x_t), f(x_s)) \leq K d_{\mathcal{T}(\Sigma)}(x_t, x_s) + C = K|t - s| + C.$$
We now check the lower bound. Pick a sequence of points in $\mathcal{T}(\Sigma, L)$

$$x_s = x_1, \ldots, x_N = x_l$$

so that $d_{\mathcal{T}(\Sigma)}(x_i, x_{i+1}) \leq r$ and $N \leq |t-s|/r + 1$. Since $W$ is always a factor in any decomposition, we know from Proposition 5.1 that

$$d_{\mathcal{T}(\Sigma')}(f(x_i)\Sigma', f(x_{i+1})\Sigma') \leq 2D_1.$$

Therefore (assuming $r \geq 4KD_1$),

$$d_{\mathcal{T}(\Sigma')}(f(x_s)W, f(x_l)W) \leq 2ND_1 \leq \frac{|t-s|}{2K} + 2D_1.$$

Now the desired lower bound in the claim follows:

$$d_{\mathcal{T}(W)}(\g(s), \g(t)) = d_{\mathcal{T}(W)}(f(x_s)W, f(x_l)W)$$

$$\geq d_{\mathcal{T}(\Sigma)}(f(x_s), f(x_l)) - d_{\mathcal{T}(\Sigma')}(f(x_s)\Sigma', f(x_l)\Sigma')$$

$$\geq \frac{1}{K} d_{\mathcal{T}(\Sigma)}(f(x_s), f(x_l)) - C - \frac{|t-s|}{2K} - 2D_1$$

$$= \frac{|t-s|}{2K} - (C + 2D_1). \quad \triangleright$$

Next, we show that if the endpoints of $g$ are close to $\partial_L(W)$, then the endpoints of $\g$ are close to the endpoints of $g$, which would imply, exactly as in the proof of Proposition 7.1, that $\g$ stays near $g$. That is, the reader should think of $w$ below as an endpoint of $g$.

**Claim 2** Let $w \in \mathcal{T}(W)$ be a point such that $d_{\mathcal{T}(W)}(w, \partial_L(W)) = R$. Then

$$d_{\mathcal{T}(W)}(f(w)\Sigma', w) \leq \frac{2LD_1}{r} + (K + 1)R + 2C. \quad (19)$$

**Proof of Claim 2** We choose a sequence of points

$$z_{\Sigma'} = u_1, \ldots, u_N$$

in $\mathcal{T}(\Sigma')$ satisfying

$$d_{\mathcal{T}(\Sigma')}(\partial_L(\Sigma'), u_N) = R \quad \text{and} \quad d_{\mathcal{T}(\Sigma')}(u_N, z_{\Sigma'}) \leq L,$$

and also

$$d_{\mathcal{T}(\Sigma')}(u_i, u_{i+1}) \leq r \quad \text{and} \quad N \leq \frac{L}{r}.$$

Let $z_i = (w, u_i)$. Note that $z_1$ is the point of interest. By Proposition 5.1, we have

$$d_{\mathcal{T}(W)}(f(z_i)W, f(z_{i+1})W) \leq 2D_1.$$
We now prove the proposition. For \( i \), we are done.

The claim follows from the last two inequalities by the triangle inequality.

Proof

The proof is essentially the same as the proof of Proposition 7.2. Let \( \mathcal{D} \) be a point such that \( \mathcal{D} \) is distance \( R \) from some point \( z_L \in \partial_L(\Sigma) \). Hence

\[
d_{\mathcal{T}(W)}(f(z_1)_W, f(z_N)_W) \leq 2ND_1 \leq \frac{2LD_1}{r}.
\]

But \( z_N \) is distance \( R \) from some point \( z_L \in \partial_L(\Sigma) \). Hence

\[
d_{\mathcal{T}(W)}(w, f(z_N)_W) \leq d_{\mathcal{T}}(z_N, f(z_N))
\]

\[
\leq d_{\mathcal{T}}(z_N, z_L) + d_{\mathcal{T}}(z_L, f(z_L)) + d_{\mathcal{T}}(f(z_L), f(z_N))
\]

\[
\leq R + C + KR + C \leq (K + 1)R + 2C.
\]

The claim follows from the last two inequalities by the triangle inequality. \( \triangle \)

We now prove the proposition. For \( i = 1, 2 \), consider geodesic segments

\[
g_i : [a_i, b_i] \to \mathcal{T}(W)
\]

such that \( g_i(0) = z_W \), \( g_i(a_i) \) and \( g_i(b_i) \) are distance \( R \) from \( \partial_L(W) \), and \( g_1 \) and \( g_2 \) make a definite size angle at \( z_W \). By Claim 1, the paths \( \bar{g}_i \) are quasigeodesics, and Claim 2 provides a bound for the distance between \( g_i(a_i) \) and \( \bar{g}_i(a_i) \) and also between \( g_i(b_i) \) and \( \bar{g}_i(b_i) \). We can make \( g_1 \) and \( g_2 \) as long as needed. If the lengths of \( g_i \) are long enough compared with the right-hand side of equation (19), this implies that \( \bar{g}_i \) stays in a uniform neighborhood of \( g_i \) and, in particular, \( f(z)_W = \bar{g}_i(0) \) is near \( g_i \) for \( i = 1, 2 \). But \( g_1 \) and \( g_2 \) make a definite size angle. Hence, \( f(z)_W \) is near \( z_W \). We are done.

Proposition 7.3

Assume either \( \mathcal{T} = \mathcal{T}(S) \), or \( \mathcal{T} = \mathcal{T}(\Sigma, L) \) and \( \Sigma \) has no component with complexity one. Let \( f : \mathcal{T} \to \mathcal{T} \) be a \((K, C)\)-quasi-isometry such that the restriction of \( f \) to the thick part is \( D_{\text{thick}} \)-close to the identity. Pick a large \( R \) so that the statements in Section 5 apply. Then there is a constant \( D_{\text{Top}} \) such that the following holds. Let \( z \in \mathcal{T} \) be a point such that

\[
d_{\mathcal{T}}(z, \mathcal{T}_{LR}) \geq \mu \eta R \quad \text{and} \quad d_{\mathcal{T}}(z, \partial_L(\Sigma)) \geq R
\]

(the second condition applies only when \( \mathcal{T} = \mathcal{T}(\Sigma, L) \)), and let \( \alpha \) be the shortest curve in \( z \), so \( \tau_z = \tau_z(\alpha) \). Then

\[
d_{\mathcal{T}(\alpha)}(z_\alpha, f(z)_\alpha) \leq D_{\text{Top}}.
\]

Proof

The proof is essentially the same as the proof of Proposition 7.2. Let \( \Sigma' = S - \alpha \) or \( \Sigma - \alpha \). For any geodesic \( g : [a, b] \to \mathcal{T}(\alpha) \) with \( g(0) = z_\alpha \) that stays \( \tau_z / \eta_0 \) away from \( \mathcal{T}_{LR} \) and \( \partial_L(\alpha) \), we let \( x' \) be a point in \( \mathcal{T} \) that projects to \( g(t) \) in \( \mathcal{T}(\alpha) \) and has the same projection to \( \Sigma' \) as \( z \). Then \( \alpha \) is still in the top group of \( x' \). Define

\[
\bar{g}(t) = f(x').
\]
Assuming $L_\Sigma$ is large enough, such geodesics exist. Also, by Proposition 6.9, we have $f_{x^*}^\tau(\alpha) = \alpha$. As in Claim 1 in Proposition 7.2, the map $\bar{g}$ is a quasigeodesic with uniform constants. We choose the end points of $g$ so that $\tau_x(\alpha) = \tau_x(\alpha) = \tau_z/\eta_0$.

Choose a sequence of points in $T(S')$, $z_{S'} = u_1, \ldots, u_N$, $d_{T(S')}(u_N, T_{thick}(S')) = \frac{\tau_z}{\eta_0}$, similar to Claim 2 in Proposition 7.2, and let $z^l \in T(S)$ be a point such that $z^l = g(a)$ and $z^l = u_i$.

As before, we have (here $\tau_z$ plays the role of $L$ in Claim 2 above)

$$d_{T(L)}(f(z^1)a, f(z^N)a) \leq \frac{2\tau_z D_1}{r}.$$

Also, using the fact that points in the thick part move by at most $D_{thick}$ and $z^N$ has a distance $\eta_0$ to the thick part, as in Claim 2 of Proposition 7.2 we have

$$d_{T(L)}(f(z^N)a, g(a)) \leq d_T(f(z^N), z^N) \leq (K + 1) \frac{\tau_z}{\eta_0} + C + D_{thick}.$$

Noting that $f(z^1) = \bar{g}(a)$, by the triangle inequality we have

$$d_{T(L)}(\bar{g}(a), g(a)) \leq \left(\frac{2D_1}{r} + \frac{K + 1}{\eta_0}\right) \tau_z + (C + D_{thick}).$$

The same holds for $\bar{g}(b)$ and $g(b)$. Note that $a < 0 < b$ and $|a|$ and $b$ are larger than $\frac{1}{2} \tau_z$. Assuming $\eta_0$ is large compared with $K$, and $\tau_z$ is large compared with the additive error in equation (20), we have that the distance between the endpoints of $\bar{g}$ and $g$ is much less than the length of $g$, and hence, $\bar{g}(0)$ is uniformly close to $g$.

Taking two such geodesics passing through $z_\alpha$ that make a definite angle with each other, we have that $f(z_\alpha)$ is uniformly close to $z_\alpha$. \hfill $\square$

**Proof of Theorem 1.2** Let $z \in T(\Sigma, L)$ be a point satisfying equation (18). Let $\Sigma'$ be the surface obtained from $\Sigma$ after removing all subsurfaces of complexity one. Let $\alpha$ be the shortest curve in $z_{\Sigma'}$. Let $\Sigma'' = \Sigma' - \alpha$.

By Proposition 7.2, for any component $W$ of $\Sigma$ with $\xi(W) = 1$ we have

$$d_{T(W)}(z_W, f(z)_W) \leq D_W.$$

For $x' \in T(\Sigma', L)$, the point $z' = (z_W, x')$ is a point in $T(\Sigma, L)$. Define, for some $\bar{L}$,

$$f_{\Sigma'}: T(\Sigma', L) \rightarrow T(\Sigma', \bar{L}), \quad f_{\Sigma'}(x') = f(z')_{\Sigma'}.$$
We will show that $f_{\Sigma'}$ is a quasi-isometry. It will also turn out that $|\tilde{L} - L| = O(1)$. We first show that $f_{\Sigma'}$ is coarsely onto. This follows from equation (21), which says that under the map $f$ the slice $\{(z_W, x') : x' \in T(\Sigma', L)\}$ is mapped a bounded distance from itself. The same is true for $f^{-1}$ and the coarse onto statement follows.

For $x', x'' \in T(\Sigma', L)$, let $z' = (x', z_W)$ and $z'' = (x'', z_W)$. Then

$$d_{T(\Sigma')}(f_{\Sigma'}(x'), f_{\Sigma'}(x'')) = d_{T(\Sigma')}(f(z'), f(z''))$$
$$\leq d_{T(\Sigma)}(f(z'), f(z''))$$
$$\leq K d_{T(\Sigma)}(z', z'') + C = K d_{T(\Sigma')}(x', x'') + C.$$

Hence, we only need to check the lower bound. It is enough to prove this for points $x'$ and $x''$ that have a distance of at least $R$ from $\mathcal{T}_L(\Sigma')$ and $\partial L(\Sigma')$. Assuming $L_\Sigma$ is large enough, such points exist and form a connected subset of $T(\Sigma', L)$. But we have shown that

$$d_{T(W)}(f(z')_W, z'_W) \leq D_W \quad \text{and} \quad d_{T(W)}(f(z'')_W, z''_W) \leq D_W.$$

Hence, since $z'_W = z''_W = z_W$,

$$d_{T(\Sigma)}(f_{\Sigma'}(x'), f_{\Sigma'}(x'')) = d_{T(\Sigma)}(f(z'), f(z''))$$
$$\geq d_{T}(f(z'), f(z'')) - d_{T(W)}(f(z')_W, f(z'')_W)$$
$$\geq \frac{1}{K} d_{T}(z', z'') - C - 2D_W$$
$$\geq \frac{1}{K} d_{T(\Sigma')}(x', x'') - (C + 2D_W).$$

That is, $f_{\Sigma'}$ is a $(K_{\Sigma'}, C_{\Sigma'})$–quasi-isometry for $K_{\Sigma'} = K$ and $C_{\Sigma'} = C + 2D_W$.

Now, Propositions 6.1 and 6.2 apply. In fact, since $f$ is anchored, we can conclude that $f_p^*$ is the identity. Hence, Proposition 6.6 implies that $f_{\Sigma'}$ is in fact $D_{\text{thick}}$–close to the identity in the thick part of $T(\Sigma', L)$. Therefore, by Proposition 7.3,

$$d_{T(\alpha)}(z_\alpha, f(z)_\alpha) \leq D_{\text{top}}.$$  

(22)

Let $L'' = \tau_{z_{\Sigma'}}(x)$. Now, for any $u \in T(\Sigma'', L'')$, let $z'_u \in T(\Sigma', L'')$ be the point that projects to $z_\alpha$ in $T(\alpha)$ and projects to $u$ in $\Sigma''$. Call the set of points $z'_u$ which project to $z_\alpha$ the slice through $z_\alpha$. At each point on the slice, $\alpha$ is the shortest curve. For some $L'''$, we can define

$$f_{\Sigma''}: T(\Sigma'', L''') \rightarrow T(\Sigma'', L'''), \quad f_{\Sigma''}(u) = f_{\Sigma'}(z'_u)_{\Sigma''}.$$
A similar argument to the one above shows that $f_{\Sigma''}$ is a quasi-isometry. Again by equation (22), both $f$ and $f^{-1}$ preserve the slice up to bounded error, which says the map $f_{\Sigma''}$ is coarsely onto. The upper and lower bounds in the definition of quasi-isometry go as before.

We next show that up to bounded additive error for any $z_u'$ in the slice, $\alpha$ is the shortest curve on $f(z_u')$. For let $\hat{\beta}$ be the shortest curve. Applying (22) to $f^{\dagger}$ we see that

$$c_{f(z_u')}(\alpha) \leq c_{f(z_u')}(\beta) \leq c_{z_u'}(\alpha) + D_{\text{Top}} \leq c_{z_u'}(\alpha) + D_{\text{Top}}.$$ 

This says that $|L'' - L''| \leq 2D_{\text{Top}}$ and so by introducing a slightly larger additive error in the constants of quasi-isometry we can assume the image of our map is in $T(\Sigma''', L'')$.

We now show that $f_{\Sigma''}$ is anchored. This is because if $u \in \partial_{L''}(\Sigma''')$, then for every $\hat{\beta} \in P_u$ we have $\tau_u(\beta) = L''$ and every curve $\beta$ is the shortest curve in $z_u'$. Then as in the proof of equation (22), the projection of $f_{\Sigma''}(u) = f_{\Sigma'}(z_u')$ to every $T(\beta)$ is also close to the projection of $z_u'$ to $T(\beta)$ which in turn is the same as the projection of $u$ to $T(\beta)$. That is, $f_{\Sigma''}(u)$ is close to $u$.

By induction (Theorem 1.2 applied to $\Sigma'''$), $f_{\Sigma''}$ is $D_{\Sigma''}$–close to the identity. We have shown that the projections of $z$ to $T(W)$, $T(\alpha)$ and $T(\Sigma'')$ are close to the projections of $f(z)$ to the same. That is, $f(z)$ is close to $z$. But the set of points satisfying equation (18) is $R$–dense in $T(\Sigma, L)$. Thus, for an appropriate value of $D_{\Sigma}$, the theorem holds.

**Proof of Theorem 1.1** The proof is the same as above. From Proposition 6.2 we have that there is an isometry of $T(S)$ such that if we precompose $f$ with this isometry, then $f_{T}^* \Sigma$ is the identity. Assuming this is done, Proposition 6.6 implies that the restriction of $f$ to $T_{\text{thick}}$ is $D_{\text{thick}}$–close to the identity.

Now consider a point $z \in T(S)$ and let $\alpha$ be the shortest curve in $z$. Choose $R$ large enough that the statements in Section 6 and Proposition 7.3 apply and so that $R \geq L_{\Sigma}$ for any subsurface $\Sigma$ of $S$. If $d_T(z, T_{LR}) \geq \mu \eta R$, then, applying Proposition 7.3,

$$(23) \quad d_T(\alpha, f(z) \alpha) \leq D_{\text{Top}}.$$ 

Let $\Sigma = S - \alpha$, let $L = \tau_z$ and, as before, for some $\tilde{L}$, define a map

$$f_{\Sigma}: T(\Sigma, L) \to T(\Sigma, \tilde{L})$$ 

as follows: For $u \in T(\Sigma, L)$, let $x \in T(S)$ be a point such that

$$x\Sigma = u \quad \text{and} \quad x\alpha = z\alpha.$$ 

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Now, define
\[ f_\Sigma(u) = f(x)_\Sigma. \]
As we argued in the proof of Theorem 1.2, this map is a quasi-isometry with uniform constants and it is anchored. Hence, by Theorem 1.2, we have
\[ d_T(\Sigma, f(z)_\Sigma, f(z)_\Sigma) \leq D_\Sigma. \]
The theorem follows from equations (23) and (24).

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