TEICHMÜLLER SPACE IS NOT GROMOV HYPERBOLIC

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The Teichmüller space of surfaces of genus $g > 1$ with the Teichmüller metric is not nonpositively curved, in the sense that there are distinct geodesic rays from a point that always remain within a bounded distance of each other ([Ma1].) Despite this phenomenon, Teichmüller space and its quotient, Moduli space, share many properties with spaces of negative curvature: for instance, most converging geodesic rays are asymptotic [Ma2], and the geodesic flow on the moduli space is ergodic [Ma3].

One can ask whether these properties can be explained by Teichmüller space having non-positive curvature in a sense weaker than that of Busemann used in [Ma1], which declared a space $X$ to be negatively curved if the endpoints of two segments from $p \in X$ are spread more than twice as far as the midpoints.

In this study of hyperbolic groups, Gromov ([Gr], see also [GdlH]) introduced a notion of negative curvature, now called Gromov hyperbolicity, that still captured many of the qualitative aspects of Riemannian negative sectional curvature, but was less restrictive than that of Busemann. Specifically, Gromov declared a space $X$ to be hyperbolic if there existed a number $M$ so that for any $p \in X$ and any triangle in $X$ with vertex at $p$, the leg of the triangle opposite $p$ would be within an $M$-neighborhood of the legs of the triangle emanating from $p$. Thus, for instance, the flat Euclidean strip $\{(x,y) \in \mathbb{R}^2 \mid 0 < x < 1\}$ would be Gromov hyperbolic but not Buseman negatively curved; moreover, the fact that there are pairs of rays emanating from $p \in T_g$ which do not diverge does not, in itself, preclude Teichmüller space with the Teichmüller metric from being Gromov hyperbolic.

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Nevertheless, the goal of this paper (Theorem 3.1) is to show that Teichmüller space is not Gromov hyperbolic. This, of course, also immediately implies that any quasi-isometric metric to the Teichmüller metric is also not Gromov hyperbolic, so any Gromov hyperbolic metric on the Teichmüller space is quite different from the Teichmüller metric.

In this connection, one needs to observe that the isometry group of the Teichmüller metric is the mapping class group ([Roy]), which contains large rank abelian subgroups, and so is not a Gromov hyperbolic group (with the word metric). This in itself does not seem to imply immediately that Teichmüller space is not Gromov hyperbolic. For example there are Kleinian groups with rank 2 abelian subgroups acting on hyperbolic 3 space, a Gromov hyperbolic space. It does suggest that good candidates for triangles to contradict Gromov’s condition might be constructed with vertices at images of a single point \( p \) under high iterates of commuting isometries.

In fact, this is the approach we take, showing (Theorem 3.1) that with respect to the Dehn twists \( \tau_{\beta_1} \) and \( \tau_{\beta_2} \) about disjoint curves \( \beta_1 \) and \( \beta_2 \) on a surface \( F \), the triangles determined by the points \( x, \tau_{\beta_1}^n \cdot x, \tau_{\beta_2}^{-n} \cdot x \) contradict Gromov’s condition: the legs of this triangle are given by the Teichmüller geodesics whose corresponding Teichmüller maps from \( x \) are described explicitly in [MM], and the distances between points on the legs are estimated from below in terms of estimates of relevant extremal lengths.

We organize our discussion as follows. In §2, we recall the background information we will need, and set the notation. In §3 we state and prove our main result.

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§2. Background and Notation.

§2.1. Teichmüller space, metric, maps. Let \( M \) be a closed \( C^\infty \) surface of genus \( g \geq 2 \); everything in this note extends to punctured surfaces with only additional notation, so we concentrate on the closed surface case. We consider the Teichmüller space \( T_g \) with the Teichmüller metric \( d(\cdot, \cdot) \). Recall that points in Teichmüller space are equivalence classes of Riemann surface structures \( S \) on \( M \), the structure \( S_1 \) is equivalent to the structure \( S_2 \) if there is a homeomorphism \( h : M \to M \), homotopic to the identity, which is a conformal map of the structures \( S_1 \) and \( S_2 \).

We define the Teichmüller distance \( d(\{S_1\}, \{S_2\}) \) by

\[
d(\{S_1\}, \{S_2\}) = \frac{1}{2} \log \inf_h K(h)
\]

where \( h : S_1 \to S_2 \) is a quasiconformal homeomorphism homotopic to the identity on \( M \) and \( K[h] \) is the maximal dilatation of \( h \). This metric is well-defined, so we may unambiguously write \( S_1 \) for \( \{S_1\} \).

An extraordinary fact about this metric is that the extremal maps, known as Teichmüller maps, admit an explicit description, as does the family of maps which describe a geodesic.

Specifically, let \( q \in \text{QD}(S) \) denote a holomorphic quadratic differential on \( S \). A horizontal (resp. vertical) trajectory is an arc along which \( q(z)dz^2 > 0 \) (resp. \( q(z)dz^2 < 0 \)) except at the zeros of \( q \). A trajectory is critical if it passes through a critical point; otherwise it is regular. If \( z \) is a local parameter near \( p \in S \) with \( q(p) \neq 0 \) and \( z(p) = z_0 \), then \( w = \int_{z_0}^z q(z)^{1/2}dz \) is the natural parameter \( q \) near \( p \).

The line element \(|q(z)|^{1/2}|dz|\) defines the \( q \)-metric on \( S \).

Teichmüller’s theorem asserts that if \( S_1 \) and \( S_2 \) are distinct points in \( T_g \), then there is a unique quasiconformal \( h : S_1 \to S_2 \) with \( h \) homotopic to the identity on \( M \) which minimizes the maximal dilatation of all such \( h \). The complex dilatation of \( h \) may be written \( \mu(h) = k \frac{dq}{|q|} \) for some non-trivial \( q \in \text{QD}(S_1) \) and some \( k, 0 < k < 1 \), and then

\[
d(S_1, S_2) = \frac{1}{2} \log(1 + k)/(1 - k).
\]

Conversely, for each \(-1 < k < 1 \) and non-zero \( q \in \text{QD}(S_1) \), the quasiconformal homeomorphism \( h_k \) of \( S_1 \) onto \( h_k(S_1) \), which has complex dilatation \( kq/|q| \), is extremal in its homotopy class. Each extremal \( h_k \) induces a quadratic differential \( q'_k \) on \( h_k(S_1) \), with critical points of \( q \) and \( q'_k \) corresponding under \( h_k \); furthermore, to the natural parameter \( w \) for \( q \) near \( p \in S_1 \) there is a natural parameter \( w'_k \) near \( h_k(p) \) so that

\[
\Re w'_k = K^{1/2} \Re w \quad \text{and} \quad \Im w'_k = K^{-1/2} \Im w,
\]

where \( K = (1 + \epsilon)/(1 - k) \).

The map \( h_k \) is called the Teichmüller extremal map determined by \( q \) and \( k \); the differential \( q \) is called the initial differential and the differential \( q_k \) is called the terminal differential. We can assume all quadratic differentials are normalized in the sense that

\[
||q|| = \int |q| = 1.
\]
The Teichmüller geodesic segment between $S_1$ and $S_2$ consists of all points $h_s(S_1)$ where the $h_s$ are Teichmüller maps on $S_1$ determined by the quadratic differential $q \in \text{QD}(S_1)$ corresponding to the Teichmüller map $h : S_1 \to S_2$ and $s \in [0, \|\mu(h)\|_\infty]$.

The mapping class group $\text{Diff}^+(M)/\text{Diff}_0(M)$ acts on $T_g$. If $\{U_\alpha, z_\alpha\}$ is an atlas defining the Riemann surface structure $S$, and $f$ is a diffeomorphism of $M$, then $f \cdot S$ is the Riemann surface structure defined by the atlas $\{f(U_\alpha), z_\alpha \circ f^{-1}\}$. The map $f : S \to f \cdot S$ is then a conformal map between these two structures.

§2.2. Modulus, Extremal length, Jenkins-Strebel Differentials, Dehn twists.

The modulus of a flat cylinder $C$ of circumference $l$ and height $h$ is $\text{mod}(C) = h/l$. For a simple closed curve $\gamma \subset M$, we define the modulus $\text{mod}_S(\gamma)$ of $\gamma$ to be the supremum of the moduli of all cylinders embedded in $M$ with core curve isotopic to $\gamma$.

The extremal length $\text{ext}_S(\gamma)$ of a curve $\gamma$ on a surface $M$ is defined to be

$$\sup_{\rho}(l_\rho([\gamma]))^2/A_\rho,$$

where $\rho$ ranges over all conformal metrics on $S$ with area $0 < A_\rho < \infty$ and $l_\rho([\gamma])$ denotes the infimum of lengths of simple closed curves homotopic to $\gamma$. One shows that $\text{ext}_S(\gamma) = 1/\text{mod } s(\gamma)$.

Kerckhoff [K] has given a characterization of the Teichmüller metric $d(S_1, S_2)$ in terms of the extremal lengths of corresponding curves on the surfaces. He proves

$$d(S_1, S_2) = \frac{1}{2} \log \sup_{\gamma} \frac{\text{ext}_S(\gamma)}{\text{ext}_{S_1}(\gamma)}$$

where the supremum ranges over all simple closed curves on $M$.

Jenkins [J] and Strebel [Str] proved the existence of quadratic differentials $q \in \text{QD}(S)$ with some prescribed trajectory topology. Specifically, they (see [Str], e.g.) showed that one could specify $m$ disjoint simple loops $\gamma_1, \ldots, \gamma_m$, with $1 \leq m \leq 3g - 3$, on $S$ representing distinct non-trivial free homotopy classes, and $m$ positive numbers $M_1, \ldots, M_m$, and that then one could find a unique (up to scalar multiple) quadratic differential $Q = Q(z)dz^2 \in \text{QD}(S)$ with the following property: if $S'$ is the result of removing the critical trajectories of $Q(z)dz^2$ from $S$, then $S'$ is the union of annuli $A_1, \ldots, A_m$ with $A_j$ homotopically equivalent to $\gamma_j$ and the modulus of $A_j$ was $M_j$, up to some fixed (independent of $j$) scalar multiple. Further $S - S'$ is the union of a finite number of analytic arcs, the smooth pieces of the critical trajectories.

Consider a point $S \in T_g$ and consider the effect of a Dehn twist $t_\alpha$ about a curve $\alpha \subset M$ yielding a point $t_\alpha \cdot S \in T_g$. It is natural to ask for a characterization of the Teichmüller map $h : S \to t_\alpha \cdot S$, or more generally, for a characterization of the Teichmüller map $h_n$ from $S \to t_\alpha^n \cdot S$ in terms of the data $\alpha$, $S$ and $n \in \mathbb{Z}$. This was described by Masur and Marden [MM] as follows. Let $q_\alpha = q_\alpha(z)dz^2$ denote the Jenkins-Strebel differential determined, as above, by $\alpha \in M$, and suppose that $\alpha \subset S$ has modulus $R$. Set

$$M = (\log R)/2\pi$$

$$\sigma_n = \tan^{-1}(2M/n)$$
and

\[ k_n = \frac{|n|/2M}{\left(1 + \left(\frac{n}{2M}\right)^2\right)^{1/2}}. \]

Then the extremal map \( h_n : S \rightarrow \tau^n_\alpha \cdot S \) is the Teichmüller map determined by \( \exp(-i(\sigma_n + \pi))|q_\alpha| \) and \( k_n \). Furthermore, if we pull back the terminal quadratic differential \( q'_\alpha \) on \( \tau^n_\alpha \cdot S \) to \( S \) via the conformal map \( \tau^n_\alpha \), then the pull-back differential \( (\tau^n_\alpha)^*q'_\alpha \) satisfies

\[
(\tau^n_\alpha)^*q'_\alpha = e^{i\theta}q_\alpha
\]

in particular the metrics \( |q_\alpha| \) and \( |(\tau^n_\alpha)^*q'_\alpha| \) agree.

§2.3. Gromov hyperbolicity. Let \( X \) be a geodesic metric space, that is, a metric space \((X, d)\) where every pair of points \( x, y \in X \) can be connected by the isometric image of the segment \([0, d(x, y)]\). In such a space, we can define the notion of a triangle with vertices \( x, y \) and \( z \in X \) to be the union of geodesic segments \([xy]\), \([yz]\), and \([xz]\) connecting \( x \) and \( y \), \( y \) and \( z \), and \( x \) and \( z \), respectively. Naturally, Teichmüller space with the Teichmüller metric is a geodesic metric space.

Gromov (see [GdlH]) introduced a notion of when such a space would share a number of qualitative properties with hyperbolic space, his definition now being commonly called “Gromov hyperbolicity”. We will say that

**Definition 2.1.** The geodesic metric space \( X \) is Gromov hyperbolic if

\[ (*) \]

There is a number \( \delta \geq 0 \) so that for every triangle \( \Delta = [xy] \cup [yz] \cup [xz] \) and every \( u \in [xy] \), we have \( d(u, [yz] \cup [xz]) \leq \delta \).

Hyperbolic space, (Riemannian) negatively curved manifolds, trees, Euclidean strips, free groups with the word metric and spheres are easily shown to be Gromov hyperbolic. On the other hand, the fundamental group of a non-compact finite volume hyperbolic \( n \)-manifold with \( n \geq 3 \), equipped with the word metric, is not hyperbolic, because of the large rank (parabolic) abelian subgroup stabilizing a point at infinity (cusp).
§3. Main Theorem.

The goal of this section is to prove

**Theorem 3.1.** Teichmüller space with the Teichmüller metric is not Gromov hyperbolic.

**Proof.** We consider a sequence of triangles $T_n$ so that there does not exist a $\delta \geq 0$ with condition ($*$) (in Definition 2.1) holding for all $T_n$.

All the triangles $T_n$ will have a common vertex $x_0 \in T_g$, chosen arbitrarily. The other vertices of the triangle $T_n$ are the points $y_1 = \tau^n_{\beta_1} \cdot x_0$ and $y_2 = \tau^{-n}_{\beta_2} \cdot x_0$, where $\beta_1$ and $\beta_2$ are disjoint simple closed curves on the surface $M$ of genus $g > 1$.

We wish to estimate the Teichmüller distance from a point $y \in [y_1 y_2]$ to the other legs $[x_0 y_1]$ and $[x_0 y_2]$. To this end, we let $J_1 dz^2 \in \text{QD}(x_0)$ be the Jenkins-Strebel differential with core curves homotopic to $\beta_1$, and we suppose that the union of its regular trajectories determine an annulus of modulus $R_1$. We let $M_1 = (\log R_1)/2\pi$, $\tan \tau_1 = 2M/n$, and $k_1 = |n|(2M_1)^{-1}(1+(n/2M_1)^2)^{-1/2}$, so that the Teichmüller map from $x_0$ to $y_1$ is determined by $\exp(-i(\tau_1 + \pi))J_1$ and $k_1$.

Let $\gamma_1$ be a simple closed curve on $M$ which crosses $\beta_1$ but not $\beta_2$, and let $\gamma_2$ be a simple closed curve on $F$ which crosses $\beta_2$ but not $\beta_1$. Then we claim

**Lemma 3.2.** For $x \in [x_0 y_1] \subset T_n \subset T_g$, the extremal length, $\text{ext}_x(\gamma_2)$, of $\gamma_2$ on $x$ is bounded independently of $n$.

**Proof of Lemma 3.2.** We begin with some more notation. Consider a quadratic differential $q \in \text{QD}(x_0)$ and the associated singular flat Euclidean metric $|q|$. For a $|q|$-geodesic segment $\alpha$, let the horizontal and vertical $q$-lengths of $\alpha$ be denoted

$$h_q(\alpha) = \int_\alpha |\Re q^{1/2}|,$$

$$v_q(\alpha) = \int_\alpha |\Im q^{1/2}|.$$

Then

$$|\alpha|_q = (h_q(\alpha))^2 + v_q(\alpha)^2)^{1/2},$$

where $|\alpha|_q$ is the $q$-length of $\alpha$. We observe that under the Teichmüller map determined by $q$ and $K$ with terminal quadratic differential $q'$, we’ll have the arc $\alpha$ remaining a $q'$-geodesic arc and

$$h_q'(\alpha) = K^{1/2}h_q(\alpha), \quad v_q'(\alpha) = K^{-1/2}v_q(\alpha) \quad \text{and} \quad |\alpha|_{q'}^2 = Kh_q(\alpha)^2 + K^{-1}v_q(\alpha)^2.$$

Of course, for fixed $h_q(\alpha)$ and $v_q(\alpha)$, equation (3.2) expresses $|\alpha|_{q'}$ as a convex function of $K > 0$.

We now specialize to the case in the statement of the lemma, where $J_1 \in \text{QD}(x_0)$ determines the Teichmüller geodesic arc $[x_0 y_1] \subset T_g$ and $J_1'$ is the terminal differential on $y_1$. Since $\tau_{\alpha}^n(\beta_1) = \beta_1$, (2.2) implies

$$|\beta_1|_{J_1} = |\beta_1|_{J_1'}.$$
The convexity of $|\beta_1|$ in $K$ along $[x_0y_1]$ forces $|\beta_1|_{J_x} < |\beta_1|_{J_1} = |\beta_1|_{J_i}$ for any of the quadratic differentials $J_x \in \text{QD}(x)$ associated to the Teichmüller geodesic segment $[x_0y_1]$ and any $x \in [x_0y_1]$. On the other hand, because a Teichmüller map is area preserving, this forces

$$\text{mod}_x(\beta_1) > \text{mod}_{x_0}(\beta_1) = \text{mod}_{y_1}(\beta_1)$$

where $\text{mod}_x(\beta_1)$ refers to the modulus of the $\beta_1$ annulus on $x \in [x_0y_1]$.

We use (3.3) in considering an alternative description of the Teichmüller map between $x_0$ and $x \in [x_0y_1]$. Specifically, by the same technique of proof as that for Lemma 2.1 in [MM] (see also the statement for the annulus in [MM; §1.3]), we can represent the Teichmüller map between $x_0$ and $x \in [x_0y_1]$ as $T_\alpha \circ S_\alpha$ where $T_\alpha$ is a “partial” Dehn twist of the initial Jenkins-Strebel annulus by an angle $2\pi\alpha$ and $S_\alpha$ is a radial expansion or (possibly) contraction of that annulus: we observe however that by (3.3), the map $S_\alpha$ is always an expansion.

Thus, we can build a model of any terminal Jenkins-Strebel differential $J_x \in \text{QD}(x)$ with $x \in [x_0y_1]$ as given by an operation of conformal plumbing followed by a partial Dehn twist, as follows. We cut the conformal cylinder along a core curve. We then glue in one cylinder to each edge of the cut, again leaving a pair of boundary components. Finally, we glue these free edges together after twisting by some angle.

The homotopy class of $\gamma_2$ is represented by a union of geodesic segments on the boundary of the Jenkins-Strebel annulus for $J_1$. Therefore, we can find an annulus $A_2$, embedded around $\gamma_2$, and also disjoint from the core curve along which our initial cut (of the previous paragraph) is made. That annulus $A_2$ will be unaffected by the plumbing and twisting, and so we can conclude that for all $x \in [x_0y_1]$ for which $x = T_\alpha \circ S_\alpha x_0$, we can find an embedded annulus $A_2$ about $\gamma_2$ of modulus bounded uniformly away from zero, independently of $n$.

Thus the extremal length of $\gamma_2$ is then uniformly bounded above, independently of $n$, concluding the proof of the lemma. □

Remark. The lemma of course holds with $\gamma_1$ and $[x_0y_2]$ in place of $\gamma_2$ and $[x_0y_1]$, by an interchange of notation in the proof.

Conclusion of the proof of Theorem 3.1. Now consider the Teichmüller geodesic arc $[y_1y_2]$. The Teichmüller map from $y_1$ to $y_2$ is given by taking a negative twist $n$ times about $\beta_1$ and about $\beta_2$. Consider the Strebel differential $Q \in \text{QD}(y_1)$ of two annuli with core curves homotopic to $\beta_1$ and $\beta_2$, of equal moduli $R$ (see [Str]). Let $M_1, n$ and $k_n$ be as in §2.2; then the Teichmüller map from $y_1$ to $y_2$ is determined by $\exp(-i(\sigma_n + \pi))Q$ and $k_n$. Let $Q'$ be the terminal differential on $y_2$.

By Lemma 3.2 and the fact that $Q$ is a competing metric in the definition of extremal length, we have

$$|v_Q(\gamma_2)| \leq |\gamma_2|_Q \leq \text{ext}_{y_1}(\gamma_2)^{1/2} = O(1).$$

Since $y_2 = \tau_{\beta_2}^{-n} \cdot x_0$, we have

$$\text{ext}_{y_2}(\gamma_2) = \text{ext}_{x_0}(\tau_{\beta_2}^{-n}(\gamma_2)).$$
Since $\tau_{\beta_2}(\gamma_2)$ crosses $\beta_2$ $n$ times, there is a constant $c_0 > 0$ so that

$$\text{ext}_{\gamma_2}(\gamma_2) \geq c_0 n^2.$$  

Moreover, since we can always compare any two normalized metrics on the fixed surface $\gamma_2$, conformally equivalent to $x_0$, we find that

(3.5) $$|\gamma_2|_{Q} \geq cn$$

for some $c > 0$.

Next, since

$$k_n = \left(1 + \left(\frac{\log R}{\pi |n|}\right)^2\right)^{-1/2}$$

we see that

(3.6) $$K_n = \frac{1 + k_n}{1 - k_n} \approx n^2$$

where $a \approx b$ if their ratio is bounded above and below away from 0. Then, applying (3.4), (3.5) and (3.6) to the identity

$$K_n h_Q(\gamma_2)^2 + K_n^{-1} v_Q(\gamma_2)^2 = |\gamma_2|_{Q'}^2$$

yields

(3.7) $$h_Q(\gamma_2) > c_2 > 0.$$  

Next, we observe that $-Q$ is the terminal quadratic differential on $y_1$ for the Teichmüller map from $y_2$ to $y_1$, with initial differential $-Q'$. Then the same argument as above shows that $h_{-Q'}(\gamma_1) > c'_2 > 0$, independently of $n$. We can then apply formula (3.2) again to conclude that $h_{-Q}(\gamma_1) > c_3 n$ for some $c_3 > 0$, which, of course, is equivalent to

(3.8) $$v_Q(\gamma_1) > c_3 n.$$

Finally, consider the point $y_* \in [y_1 y_2]$ determined by the Teichmüller map defined by $Q$ with $K^{1/2} = \sqrt{n}$; let $Q_* \in \text{QD}(y_*)$ denote the terminal differential. Then (3.7) and (3.8), along with the relationship (3.2) show that

$$|\gamma_2|_{Q_*} \geq h_{Q_*}(\gamma_2) \geq c_2 \sqrt{n} \quad \text{and} \quad |\gamma_1|_{Q_*} \geq v_{Q_*}(\gamma_1) \geq c_3 \sqrt{n}.$$

Since $Q_*$ is a competing metric for extremal length, $\text{ext}_{y_*}(\gamma_i) \geq |\gamma_i|_{Q_*}^2 > c_4 n$.

Finally, we apply Kerckhoff’s formula (2.1) and Lemma 3.2 to estimate the Teichmüller distance $d([x_0 y_1], y_*):$ we see that since $\text{ext}_{y_*}(\gamma_2) > c_4 n$ while $\text{ext}_x(\gamma_2) < c_5$ for $x \in [x_0 y_1]$, then (2.1) forces $d(x, y_*) > \frac{1}{2} \log(c_5^{-1} c_4 n)$. Since an analogous estimate holds for $d([x_0 y_2], y_*)$, we see that the defining condition $(\ast)$ of Definition 2.1 of Gromov hyperbolicity does not hold.
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