Quasisymmetric nonparametrization 
and spaces associated with the Whitehead continuum

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The decomposition space \( \mathbb{R}^3/\text{Wh} \) associated with the Whitehead continuum \( \text{Wh} \) is not a manifold, but the product \((\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m\) is homeomorphic to \( \mathbb{R}^{3+m} \) for any \( m \geq 1 \) (known since the 1960’s). We study the quasisymmetric structure on \((\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m\) and show that the space \((\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m\) may be equipped with a metric resembling \( \mathbb{R}^{3+m} \) geometrically and measure theoretically—it is linearly locally contractible and Ahlfors \((3+m)\)-regular—nevertheless the resulting space does not admit a quasisymmetric parametrization by \( \mathbb{R}^{3+m} \).

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In memory of Juha Heinonen, an extraordinary mathematician and friend, who passed away after the mathematical work in this paper was completed. – J-M W

1 Introduction

To understand the underlying structure of a metric space, one seeks a parametrization of a special type. The classical Riemann mapping theorem is an example. The problem of characterizing metric \( n \)-spheres that are bi-Lipschitz equivalent to the standard sphere \( S^n \), or quasisymmetrically equivalent to \( S^n \), has received considerable attention in recent years. Despite a large number of results (for example by Bonk and Kleiner [6], David and Semmes [10], Heinonen and Koskela [18], Laakso [22] and Semmes [29; 31; 32]), the question is still far from being understood.

There exist finite \( 5 \)-dimensional polyhedra that are homeomorphic to the standard sphere \( S^5 \) but not bi-Lipschitz equivalent to \( S^5 \)—an observation of Siebenmann and Sullivan [34] based on deep work of Cannon [7] and Edwards [12; 11], which asserts that the double suspension \( \Sigma^2 H^3 \) of a \( 3 \)-dimensional homology sphere \( H^3 \) with a nontrivial fundamental group is homeomorphic to the standard sphere \( S^5 \). The double suspension \( \Sigma^2 H^3 \) can be considered as the join \( S^1 \ast H^3 \), where \( H^3 \) is triangulated and \( \Sigma^2 H^3 \) is equipped with a natural barycenter metric. The complement of the suspension circle \( S^1 \) in \( \Sigma^2 H^3 \) is not simply connected; therefore every homeomorphism \( f \)
from $\Sigma^2H^3$ onto $S^5$ must map $S^1$ onto a curve $f(S^1)$ whose complement in $S^5$ is not simply connected. Consequently $f(S^1)$ has positive 3–dimensional Hausdorff measure. Hence $f$ cannot be Hölder continuous of order greater than $1/3$ and is not bi-Lipschitz. It was then asked by Siebenmann and Sullivan [34] whether there exists a quasisymmetric homeomorphism between $\Sigma^2H^3$ and $S^5$, a question which seems inaccessible at the moment.

We study a problem in a similar spirit and, in some sense, of one dimension lower. Let $Wh$ denote a Whitehead continuum in $\mathbb{R}^3$ (see Whitehead [39]) and $\mathbb{R}^3/Wh$ be the decomposition space associated with $Wh$ obtained by collapsing $Wh$ to a point $q$ while leaving all other points unchanged. The resulting space $\mathbb{R}^3/Wh$ endowed with the quotient topology is not a manifold at $q$, therefore is not homeomorphic to $\mathbb{R}^3$; however the product space $(\mathbb{R}^3/Wh) \times \mathbb{R}^1$ is homeomorphic to $\mathbb{R}^4$ (see Bing [4; 5]).

The complement of $\{q\} \times \mathbb{R}^1$ in $(\mathbb{R}^3/Wh) \times \mathbb{R}^1$ is not simply connected at $\{q\} \times \mathbb{R}^1$. Therefore any homeomorphism $f$ from $(\mathbb{R}^3/Wh) \times \mathbb{R}^1$ onto $\mathbb{R}^4$ maps $\{q\} \times \mathbb{R}^1$ to an infinite arc, which is wild in $\mathbb{R}^4$ and necessarily has positive 2–dimensional Hausdorff measure. Hence $f$ cannot be Hölder continuous of order greater than $1/2$.

Semmes [31, page 206] constructed a manifold $\tilde{M}$ modeled on $\mathbb{R}^3/Wh$ and showed that $\tilde{M}$ can be realized as a linearly locally contractible (resembling $\mathbb{R}^3$ geometrically) and Ahlfors 3–regular (resembling $\mathbb{R}^3$ measure theoretically) subset of $\mathbb{R}^4$; on the other hand $\tilde{M}$ is not quasisymmetrically equivalent to $\mathbb{R}^3$. Heinonen and Semmes [20] asked the following question: When $(\mathbb{R}^3/Wh) \times \mathbb{R}^m$ is equipped with a linearly locally contractible and Ahlfors $(3+m)$–regular metric, does $(\mathbb{R}^3/Wh) \times \mathbb{R}^m$ then admit a quasisymmetric parametrization by $\mathbb{R}^{3+m}$ for some $m \geq 1$? We answer this question in the negative using essentially a product of the Semmes metric with the Euclidean metric.

1.1 Theorem For any $m \geq 1$, the metric space $(\mathbb{R}^3/Wh) \times \mathbb{R}^m$, though homeomorphic to $\mathbb{R}^{3+m}$, can be equipped with a metric that is linearly locally contractible and Ahlfors $(3+m)$–regular so that the resulting space does not admit a quasisymmetric parametrization by $\mathbb{R}^{3+m}$.

The deeper reason for the nonexistence of the quasisymmetric parametrization in Theorem 1.1 is the fact that the meridians of the solid tori used in construction of the Whitehead continuum $Wh$ are trivial in homology of the complement of $Wh$, but nontrivial in homotopy.

We now proceed to give the formal definitions.

A homeomorphism $f: X \to Y$ between two metric spaces is said to be *bi-Lipschitz* if there is a constant $C \geq 1$ so that

$$C^{-1}|x - y| \leq |f(x) - f(y)| \leq C|x - y|$$

for all $x, y$ in $X$. A homeomorphism $f: X \to Y$ between two metric spaces is said to be *quasisymmetric* if there is a homeomorphism $\eta: [0, \infty) \to [0, \infty)$ so that

$$|x - a| \leq t|x - b| \implies |f(x) - f(a)| \leq \eta(t)|f(x) - f(b)|$$

for all triples of points $x, a, b$ in $X$ and for all $t > 0$ (see Tukia and Väisälä [35]). Quasisymmetric maps distort relative distance by a finite amount and distort distance roughly the same in all directions. They are, in some sense, appropriate generalizations of conformal mappings for metric spaces.

A metric space is said to be *linearly locally contractible* if there is a constant $C \geq 1$ so that each metric ball of radius $0 < r < C^{-1}$ in the space can be contracted to a point inside the ball of same center with radius $Cr$. Linear local contractibility is a geometric condition; it is necessarily satisfied if a metric space is quasisymmetrically equivalent to $\mathbb{R}^n$.

A metric space $X$ is said to be *Ahlfors $Q$–regular* if there is a Borel measure $\mu$ such that

$$C^{-1}r^Q \leq \mu(B_r) \leq Cr^Q$$

for some constants $Q > 0$ and $C \geq 1$, and for all closed balls $B_r$ of radius $0 < r \leq \text{diam } X$. In this case, $X$ has Hausdorff dimension $Q$ and (1.2) holds when $\mu$ is replaced with the Hausdorff $Q$–measure of $X$ (possibly with a different constant $C$). When $Q$ is an integer, the space $X$ resembles $\mathbb{R}^Q$ measure theoretically but may be totally disconnected. A metric space may be quasisymmetrically equivalent to $\mathbb{S}^Q$ but not $Q$–regular; the von Koch snowflake curve is an example.

A theorem of Semmes [30] states that if a linearly locally contractible topological $Q$–manifold is Ahlfors $Q$–regular, then it satisfies a $(1, 1)$–Poincaré inequality, hence it has nice analytical properties.

Tukia and Väisälä [35] have shown that a *metric doubling space* $(X, d)$ homeomorphic to $\mathbb{S}^1$ is quasisymmetrically equivalent to $\mathbb{S}^1$ if and only if $X$ satisfies the Ahlfors 2–point condition [35].

Bonk and Kleiner [6] have given a necessary and sufficient condition for a doubling metric space to be quasisymmetrically equivalent to $\mathbb{S}^2$. With this they proved the following theorem: A linearly locally contractible metric 2–sphere is quasisymmetrically equivalent to $\mathbb{S}^2$ if it is Ahlfors 2–regular.
Semmes [31] showed that the theorem of Bonk and Kleiner fails in dimension 3 for a geometrical realization of the decomposition space associated with the Bing double in $\mathbb{R}^3$, and for the manifold $\tilde{M}$ mentioned earlier. Theorem 1.1 shows that these natural conditions for quasisymmetric parametrization are also insufficient in dimension 4 and higher.

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### 2 Whitehead continuum

In 1935, J H C Whitehead [39] discovered a contractible noncompact $3$–manifold in $S^3$ that is not homeomorphic to $\mathbb{R}^3$. The complement of this manifold is now called a Whitehead continuum. Topological properties and pictures accompanying the construction of a Whitehead continuum can be found in Daverman [9], Kirby [21] and Semmes [33].

Given a set $E$ in $\{x_1 = 0, x_2 \geq 0\} \subset \mathbb{R}^3$, with a slight abuse of notation, denote by $S^1 \times E$ the solid of revolution $\{(x_1, x_2, x_3) : (0, (x_1^2 + x_2^2)^{1/2}, x_3) \in E\}$ in $\mathbb{R}^3$. Let $B_0^2$ (resp. $\partial B_0^2$) denote the closed disk (resp. the circle) in $\{x_1 = 0\} \subset \mathbb{R}^3$ having center $(0, 1, 0)$ and radius $\frac{1}{2}$.

A simple closed curve $\alpha$ on $S^1 \times \partial B_0^2$ is a **meridian** (resp. a **longitude**) of the torus $S^1 \times B_0^2$ if there exists a homeomorphism from $\partial B_0^2$ (resp. $S^1 \times \{(0, \frac{1}{2}, 0)\}$) onto $\alpha$ which is homotopic in $S^1 \times \partial B_0^2$ to the identity map on $\partial B_0^2$ (resp. $S^1 \times \{(0, \frac{1}{2}, 0)\}$).

Let $T_0$ be a smooth compact solid torus embedded in $\mathbb{R}^3$, identified with $S^1 \times B_0^2$ for convenience. Let $T_1$ be a second compact solid torus smoothly embedded in the interior of $T_0$ and positioned in such a way that $T_1$ and any meridian of $T_0$ form a Whitehead link (see Kirby [21] and Rourke and Sanderson [27]). Note that $T_1$ is contractible in $T_0$, but the contraction of $T_1$ can not take place without crossing itself. In fact, $T_1$ is knotted in $T_0$ but is not knotted in $\mathbb{R}^3$. Let $\phi$ be a diffeomorphism defined in a neighborhood of $T_0$ that maps $T_0$ onto $T_1$. Define inductively for $k \geq 2$,

$$T_k = \phi(T_{k-1}).$$
The intersection
\[ Wh = \bigcap_{k=0}^{\infty} T_k \]
is a Whitehead continuum. The continuum \( Wh \) is one-dimensional and is contractible inside each \( T_k, k \geq 0 \). Identify \( S^3 \) with \( \mathbb{R}^3 \cup \{ \infty \} \) in topology. The Whitehead manifold \( S^3 \setminus Wh \) is simply connected and in fact contractible [21].

The Whitehead link is symmetric. For \( k \geq 1 \), there is a homeomorphism of \( S^3 \) that interchanges a meridian of \( T_k \) with a core of \( T_{k+1} \) (such as \( \phi^{(k+1)}(S^1 \times \{0, 1, 0\}) \)). However the homeomorphism reversing the link can not be confined to \( T_0 \) (see Kirby [21, page 83]). Therefore there are loops, namely the meridians of \( T_k \), lying arbitrarily close to the Whitehead continuum \( Wh \) that can not be contracted in \( S^3 \setminus Wh \) to a point while staying near \( Wh \). In other words the Whitehead manifold \( S^3 \setminus Wh \) is not simply connected at \( Wh \), so \( S^3 \setminus Wh \) is not homeomorphic to \( \mathbb{R}^3 \).

The decomposition space \( \mathbb{R}^3 / Wh \) is defined by collapsing \( Wh \) to a single point, called \( q \), while keeping all other points unchanged, then endowed with the quotient topology. The resulting space is not a manifold at the quotient point \( q \) by the previous discussion, hence it is not homeomorphic to \( \mathbb{R}^3 \).

Taking the product with \( \mathbb{R}^m (m \geq 1) \) however destroys all nonmanifold points; as a consequence \( (\mathbb{R}^3 / Wh) \times \mathbb{R}^m \) is homeomorphic to \( \mathbb{R}^{3+m} \) (by Andrews and Rubin [3], also credited to Arnold Shapiro by Bing [4; 5]). See Daverman [9] and Kirby [21] for more discussions about products of decompositions with a line.

Let \( \pi: \mathbb{R}^3 \rightarrow \mathbb{R}^3 / Wh \) be the quotient map defined by \( \pi(Wh) = q \) and \( \pi(x) = x \) if \( x \notin Wh \); for simplicity denote by
\[ \tilde{E} = \pi(E) \]
the image of a set \( E \) under \( \pi \). Let
\[ \mathcal{L} = \{q\} \times \mathbb{R}^m. \]

A curve \( \gamma \) on \( \partial \tilde{T}_k \) is called a meridian (resp. a longitude) of \( \tilde{T}_k \) if \( \pi^{-1} \gamma \) is a meridian (resp. a longitude) of \( T_k \). The noncontractibility of the meridians of \( T_k \) in the Whitehead manifold near \( Wh \) implies the following.

2.1 Proposition Meridians of \( \tilde{T}_k \) are not contractible in \( \tilde{T}_0 \setminus \{q\} \), and meridians of \( \tilde{T}_k \times \{z\} \) are not contractible in \( (\tilde{T}_0 \times \mathbb{R}^m) \setminus \mathcal{L} \), for any \( m \geq 1, k \geq 1 \) and \( z \in \mathbb{R}^m \).

On the other hand, a meridian of \( \tilde{T}_k \) bounds a surface (a disk with a handle) in \( \tilde{T}_k \setminus \{q\} \). The difference of the roles of a meridian in homotopy and in homology is important in our proof.
We define a metric on the decomposition space $\mathbb{R}^3/\text{Wh}$ by adapting that of Semmes in [31]. The metric to be defined has a self-similarity property and sizes of $\mathcal{T}_k$ decrease geometrically towards the point $q$. Semmes embedded $\mathbb{R}^3/\text{Wh}$ in $\mathbb{R}^4$ which is more visual; we consider $(\mathbb{R}^3/\text{Wh})\setminus\{q\}$ as an abstract manifold on which the metric can be explicitly described.

Fix a number $c_0 \in (0, \frac{1}{\sqrt{2}})$. Let $P_0 = (0, 1, 0)$, and $A = \{x \in \{0\} \times \mathbb{R}^2 : \frac{1}{2} - 2c_0 < |x - P_0| \leq \frac{1}{2} - c_0\}$. $A' = \{x \in \{0\} \times \mathbb{R}^2 : \frac{1}{2} - 2c_0 < |x - P_0| < \frac{1}{2} + 2c_0\}$ and $A'' = \{x \in \{0\} \times \mathbb{R}^2 : \frac{1}{2} - 3c_0 < |x - P_0| < \frac{1}{2} + 3c_0\}$ be three annuli in $\{0\} \times \mathbb{R}^2$. Let 

$$U_0 = S^1 \times A, \quad V_0 = S^1 \times A' \quad \text{and} \quad W_0 = S^1 \times A''$$

be the solids obtained by revolving $A, A'$ and $A''$ about the $x_3-$axis. Note that $V_0$ and $W_0$ are neighborhoods of $\partial T_0$ and that $U_0 \subset T_0 \cap V_0 \subset V_0 \subset W_0$. Recall that $\phi$ is a diffeomorphism defined in a neighborhood of $T_0$ that maps $T_0$ onto $T_1$. Assume that $c_0$ has been chosen small enough so that $W_0$ is contained in the neighborhood of $T_0$ on which $\phi$ is defined and that $\phi(T_0 \cup W_0) \subset T_0 \setminus W_0$, thus $T_1$ is contained in $T_0 \setminus W_0$. Define inductively for $k \geq 1$,

$$U_k = \phi(U_{k-1}), \quad V_k = \phi(V_{k-1}) \quad \text{and} \quad W_k = \phi(W_{k-1})$$

and define for $k \geq 0$, closed regions between $V_k$ and $V_{k+1}$

$$\Theta_k = T_k \setminus (T_{k+1} \cup V_k \cup V_{k+1}),$$

and solid tori

$$t_k = T_k \setminus (V_k \cup U_k).$$

Note that

$$T_{k+1} \subset t_k \subset T_{k}.$$

Fix a parameter $a \in (0, 1)$. Define a metric $d_a$ on the Whitehead continuum $\mathbb{R}^3 \setminus \text{Wh}$ as follows. Initially, define a matrix $(\lambda_{ij}) = \text{Id}$ on $(\mathbb{R}^3 \setminus T_0) \cup W_0$ and define for $k \geq 1$,

$$(\lambda_{ij}) = a^{2k} (D\phi^{(-k)})^{T} D\phi^{(-k)} \quad \text{in} \quad W_k$$

where $\phi^{(-k)}$ is the $k-$th iterate of $\phi^{-1}$. Later, adjust $(\lambda_{ij})$ in $\bigcup_{k=0}^{\infty} (W_k \setminus V_k)$ and extend $(\lambda_{ij})$ to $\mathbb{R}^3 \setminus \text{Wh}$ so as to achieve the smoothness, the positive definiteness of $(\lambda_{ij})$ and the self-similarity (3.3) below, and to preserve the previously defined values on $(\mathbb{R}^3 \setminus T_0) \cup \bigcup_{k=0}^{\infty} V_k$. This can be accomplished by first extending $(\lambda_{ij})$ continuously to $\Theta_0 \setminus (W_0 \cup W_1)$ with the aid of partition of unity, next smoothing $(\lambda_{ij})$ in $\Theta_0$ by convolution with a kernel that varies with the Euclidean distance $\text{dist}(x, \partial \Theta_0)$, and finally redefining $(\lambda_{ij})$ in $\bigcup_{k=1}^{\infty} \Theta_k$ so that for each $k \geq 1$,

$$(\lambda_{ij}) = a^{2k} (D\phi^{(-k)})^{T} (\lambda_{ij}(\phi^{(-k)})) D\phi^{(-k)} \quad \text{in} \quad \Theta_k.$$
The metric $d_a$ on $\mathbb{R}^3 \setminus Wh$ associated with the matrix $(\lambda_{ij})$ is defined by
\[ d_a(x, y) = \inf \{ \text{length } \gamma : \gamma \text{ continuously differentiable curve joining } x \text{ and } y \}, \]
where
\[ \text{(3.2)} \quad \text{length } \gamma = \int_\gamma \sqrt{\sum \lambda_{ij} dx_i dx_j}. \]

The metric thus defined is self-similar with respect to $Wh$ in the following sense:
\[ d_a(x, y) = a^k d_a(\phi^{(-k)}x, \phi^{(-k)}y) \quad \text{for all } x \in T_k, \quad y \in T_{k'}, \]
and for all $k', k'' \geq k \geq k \geq 0$ for some $k$ depending only on $\phi$ and $c_0$.

The metric on the decomposition space $\mathbb{R}^3 / Wh$, again called $d_a$, is the pushforward metric induced by the homeomorphism $\pi : \mathbb{R}^3 / Wh \to (\mathbb{R}^3 / Wh) \setminus \{q\}$ followed by the continuous extension to the point $q$.

Denote by $d_e$ be the Euclidean metric on $\mathbb{R}^m$ for any $m \geq 1$. Let $\delta_a$ be the metric on the product space $(\mathbb{R}^3 / Wh) \times \mathbb{R}^m$ defined by
\[ \delta_a((x, x'), (y, y')) = d_a(x, y) + d_e(x', y') \]
for all $(x, x'), (y, y') \in (\mathbb{R}^3 / Wh) \times \mathbb{R}^m$ and any $m \geq 1$.

Here, as well as in the future, we use $c$, $c_1, c_2, \ldots, C, C_{1}, C_{2}, \ldots, C', C''$, \ldots to denote positive constants depending at most on $m, \phi, c_0$ and $a$, in particular, independent of $k$. We use $r \leq s, r \geq s, r \sim s$ to mean that the ratio $\frac{r}{s}$ is bounded above, or bounded below, or bounded above and below by this type of constants. Values of $c$ and $C$ need not be the same at each occurrence.

Note then
\[ \text{(3.5)} \quad \text{diam}_{d_a}(\overline{T}_k) \simeq a^k, \]
\[ \text{(3.6)} \quad \text{dist}_{d_a}(\overline{t}_k, \partial \overline{T}_k) = \text{dist}_{d_a}(\overline{v}_k, \partial \overline{T}_k) = c_0 a^k, \]
\[ \text{(3.7)} \quad \text{dist}_{d_a}(q, \partial \overline{T}_k) \simeq \text{dist}_{d_a}(\partial \overline{T}_k, \partial \overline{T}_{k+1}) \simeq \text{dist}_{d_a}(\overline{v}_k, \overline{v}_{k+1}) \simeq a^k. \]

We now give a concrete reformulation of Theorem 1.1.

3.8 Theorem The metric space $(\mathbb{R}^3 / Wh) \times \mathbb{R}^m, \delta_a)$ is linearly locally contractible and Ahlfors $(3+m)$–regular. However there is no quasisymmetric homeomorphism between $(\mathbb{R}^3 / Wh) \times \mathbb{R}^m, \delta_a)$ and $\mathbb{R}^{3+m}$, when $a > 2^{-(3+m)/2m}$ and $m \geq 1$. 
The restriction on $a$ in the theorem is a consequence of the modulus estimates. It is unclear whether the theorem remains true for the whole range of $a \in (0, 1)$.

The linear local contractibility and the Ahlfors regularity in Theorem 3.8 follow from (3.3)–(3.7) and a lifting-twisting-shrinking procedure used in proving the topological equivalence between $(\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m$ and $\mathbb{R}^{3+m}$. By (3.3), (3.5), (3.6) and (3.7), there exists a large constant $C > 1$ such that for each ball $B_{da}(x, r)$ in $(\mathbb{R}^3/\text{Wh}, da)$, one of the following holds:

(i) $x = q$.

(ii) $x \in \bar{T}_k \setminus \bar{T}_{k+1}$ for some $k \geq -1$ and $q \in B_{da}(x, Cr)$; in this case $B_{da}(x, r) \subset B_{da}(q, C' r) \subset B_{da}(x, C''r) \subset B_{da}(q, C''r)$.

(iii) $x \in \bar{T}_k \setminus \bar{T}_{k+1}$ for some $k \geq -1$ and $q \notin B_{da}(x, Cr)$; in this case $B_{da}(x, r) \subset \bar{T}_{k-1} \setminus \bar{T}_{k+2}$ and there is an open set $U$ homeomorphic to a Euclidean ball so that

$$B_{da}(x, r) \subset U \subset B_{da}(x, Cr).$$

Here, with a slight abuse of notation, $\bar{T}_{-1}$ denotes $\mathbb{R}^3/\text{Wh}$. By (3.4), there exists $C > 1$ so that

$$B_{\delta a}((q, (0, 0, \ldots, 0)), C^{-1}a^k) \subset \bar{T}_k \times [-a^k, a^k] \subset B_{\delta a}((q, (0, 0, \ldots, 0)), C a^k).$$

We first check that $\bar{T}_1 \times [-1, 1]^m$ is contractible inside $\bar{T}_0 \times [-4, 4]^m$. It is known that the quotient map $\pi \times \text{id}: \mathbb{R}^{3+m} \to (\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m$ can be uniformly approximated by homeomorphisms (see Daverman [9, pages 81–84]). Choose $g: \mathbb{R}^{3+m} \to (\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m$, a homeomorphism satisfying

$$\text{dist}_{\delta a}(g(x, z), (\pi \times \text{id})(x, z)) < c_0/30 \text{ on } \mathbb{R}^{3+m}.$$

Then $g^{-1}(\bar{T}_1 \times [-1, 1]^m)$, a subset of $(T_1 \cup V_1) \times [-2, 2]^m$, is contractible inside $t_0 \times [-3, 3]^m$. Hence $\bar{T}_1 \times [-1, 1]^m$ is contractible in $g(t_0 \times [-3, 3]^m) \subset \bar{T}_0 \times [-4, 4]^m$. The linear local contractibility of $((\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m, \delta a)$ can be seen by scaling and examining the projection of a given ball $B_{\delta a}(x, r)$ into $\mathbb{R}^3/\text{Wh}$ for the three alternative cases.

Define a measure $\mu$ on $\mathbb{R}^3 = \text{Wh} \cup (\mathbb{R}^3 \setminus \text{Wh})$ as follows: $\mu(\text{Wh}) = 0$, $\mu((\mathbb{R}^3 \setminus T_1)$ is the Lebesgue measure, and

$$\mu(E) = a^{3k} \mu(\phi^{-k}(E))$$

if $E \subset T_k \setminus T_{k+1}$ and $k \geq 1$. The measure on the decomposition space $(\mathbb{R}^3/\text{Wh}, da)$, again called $\mu$, is defined to be the pushforward of the measure $\mu$ on $\mathbb{R}^3$ induced by

the quotient map $\pi: \mathbb{R}^3 \to \mathbb{R}^3/\text{Wh}$. Note from (3.3) that
\[
\mu(\tilde{T}_k/\tilde{T}_{k+1}) \simeq a^{3k} \quad \text{for } k \geq 0,
\]
and that $\mu(B_{d_\alpha}(q, r)) \simeq r^3$; and note from (3.3) and the smoothness of $(\lambda_{ij})$ that $\mu(B_{d_\alpha}(x, r)) \simeq r^3$ if $B_{d_\alpha}(x, r) \subset \tilde{T}_{k-1}/\tilde{T}_{k+2}$ and $k \geq 0$. The Ahlfors 3–regularity of $(\mathbb{R}^3/\text{Wh}, d_\alpha)$ follows by checking the three alternative cases. The product space $((\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m, \delta_\alpha, \mu \times dx)$ is Ahlfors $(3+m)$–regular equipped with the product of $\mu$ with the Lebesgue measure $dx$ in $\mathbb{R}^m$.

4 Modulus of surface families

Let $f$ be a homeomorphism from $((\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m, \delta_\alpha)$ onto $\mathbb{R}^{3+m}$. What is the obstruction for quasisymmetry? We give a heuristic explanation for $m = 1$. Proposition 2.1 implies that $B_n \setminus \mathcal{L}$ is not simply connected for any small ball $B$ in $(\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^1$ that intersects $\mathcal{L}$. Hence $f(B) \setminus f(\mathcal{L})$ is not simply connected and $f(\mathcal{L})$ is wild in $\mathbb{R}^4$. A theorem of Martio, Rickman and Väisälä (Theorem 9.1 in the Appendix) then implies that the 2–dimensional Hausdorff measure
\[
\mathcal{H}^2(f(B) \cap f(\mathcal{L})) > 0,
\]
for any ball $B$ in $(\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^1$ that intersects $\mathcal{L}$. One would then expect that $f$ maps all line segments of the form $\{z\} \times (t, t + s)$ in $(\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^1$ near $\{q\} \times \mathbb{R}^1$ to curves of much greater length. A comparison of moduli of suitable curve families in the domain and their images would prevent $f$ from being quasisymmetric. Nevertheless we are unable to provide quantitative estimates for the lengths of $f(\{z\} \times (t, t + s))$; so we shall work with the modulus of surface families instead.

The modulus of curve families has been an important tool in geometric function theory since the 1920’s, first used by Grötzsch and Teichmüller and later extensively studied by Beurling and Ahlfors [1]. Extending the concept of modulus from curve families to $l$–dimensional surface families in $\mathbb{R}^n$ was due to Fuglede [15]. We need the notion of modulus for surface families in the setting of metric spaces. We shall not aim for full generality though.

Let $(X, d)$ be a linearly locally contractible topological $n$–manifold that is also Ahlfors $n$–regular. Let $1 \leq l \leq n - 1$, $p$ a real number $\geq 1$ and $\mathcal{S}$ be a family of topological $l$–manifolds in $X$. A nonnegative Borel function $\rho: X \to [0, \infty]$ is called admissible for $\mathcal{S}$ if
\[
\int_{\Gamma} \rho(x)d\mathcal{H}_d^l(x) \geq 1
\]
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for every $\Gamma \in \mathcal{S}$ that has positive Hausdorff $l$–measure $\mathcal{H}^l_d(\Gamma)$ and is locally finite with respect to $\mathcal{H}^l_d$. The $p$–modulus of $\mathcal{S}$ is defined by

$$\text{Mod}_p \mathcal{S} = \inf \int_X \rho^p(x) d\mathcal{H}^n_d(x),$$

where the infimum is taken over all admissible $\rho: X \to [0, \infty]$. Here and later, we denote by $\mathcal{H}^l_d$ the $i$–th dimensional Hausdorff measure with respect to the metric $d$. We omit the subscript $d$ if the metric is the Euclidean one.

The most important modulus from the point of view of (quasi)conformal geometry is the $n/l$–modulus $\text{Mod}_{n/l}$. It is conformally invariant and hence called the conformal modulus. The conformal modulus of curve families is quasi-invariant under quasisymmetric maps. This was proved by Gehring [16] for the Euclidean $n$–spaces and by Heinonen and Koskela [19] for very general metric spaces.

We consider a sequence of $(1+m)$–dimensional surface families $\mathcal{S}_k$ in $(\mathbb{R}^3/Wh) \times \mathbb{R}^m$ defined as follows. First we select the curve family

$$C = \{ S^1 \times \{x\} : x \in A \}$$

in $T_0 \subset \mathbb{R}^3$, where $A$ is the planar annulus defined in Section 3. Let

$$C_k = \{ \pi \phi^{(k)}(S^1 \times \{x\}) : x \in A \} \quad \text{for } k \geq 0,$$

be the associated curve families in the decomposition space $\mathbb{R}^3/Wh$, then define the surface families

$$\mathcal{S}_k = \{ \gamma \times [0, 1]^m : \gamma \in C_k \} \quad \text{for } k \geq 0,$$

in $(\mathbb{R}^3/Wh) \times \mathbb{R}^m$ by taking products.

We prove a one-sided inequality for the conformal moduli, which is adequate for our purpose. Constants depending on $f$ as well as $m, \phi, c_0$ and $a$, shall be denoted by $C_f$.

4.1 Proposition Let $f$ be a quasisymmetric homeomorphism from $(\mathbb{R}^3/Wh) \times \mathbb{R}^m$ onto $\mathbb{R}^{3+m}$. Then there exists a constant $C(f) > 0$ such that

$$\text{Mod}_{(3+m)/(1+m)} \mathcal{S}_k \leq C(f) \text{Mod}_{(3+m)/(1+m)} f(\mathcal{S}_k) \quad \text{for all } k \geq 0.$$

Proof Since the matrix $(\lambda_{ij})$ is smooth in $\mathbb{R}^3/Wh$, the quasisymmetric map $f$ is in $W^{1,r}_{\text{loc}}((\mathbb{R}^3/Wh) \times \mathbb{R}^m)\setminus \mathcal{L}$ for some $r > 3 + m$; this can be seen by following the proof of the theorem of Gehring [17] on the higher integrability of the derivatives of quasiconformal maps in Euclidean spaces. Hence $f$ is differentiable $\mathcal{H}^{3+m}_{\delta_a}$–almost everywhere in $(\mathbb{R}^3/Wh) \times \mathbb{R}^m$. Set, for $x \in A$,

$$\Gamma_x = \pi \phi^{(k)}(S^1 \times \{x\}) \times [0, 1]^m.$$
In Euclidean spaces, quasiconformal mappings are absolutely continuous on almost all lines. Adapting the standard proof of this fact [36, Theorem 31.2], we may conclude that for $H^2$–almost every $x \in A$, $f|\Gamma_x$ maps sets of $\mathcal{H}^{1+m}_{\delta_a}$–measure zero to sets of $\mathcal{H}^{1+m}$–measure zero. We may then conclude that for any nonnegative Borel function $\rho$ on $\mathbb{R}^{3+m}$ and for $H^2$–almost every $x \in A$,

$$\int_{\Gamma_x} \rho(f(x)) |Df(x)|^{1+m} d\mathcal{H}^{1+m}_{\delta_a}(x) \geq \int_{f(\Gamma_x)} \rho(y) d\mathcal{H}^{1+m}(y),$$

by adapting the standard argument for quasiconformal maps [36, Theorem 5.3]. Quasisymmetry implies that

$$\int_{(R^3/Wh) \times R^m} (\rho(f(x)) |Df(x)|^{1+m})^{(3+m)/(1+m)} d\mathcal{H}^{3+m}_{\delta_a}(x) \leq C(f) \int_{(R^3/Wh) \times R^m} \rho(f(x))^{(3+m)/(1+m)} |\det Df(x)| d\mathcal{H}^{3+m}_{\delta_a}(x) \leq C(f) \int_{R^{3+m}} \rho(y)^{(3+m)/(1+m)} d\mathcal{H}^{3+m}(y).$$

From the fact that the union of these surfaces has $\mathcal{H}^{3+m}_{\delta_a}$–measure zero, it follows that the exceptional surfaces for which (4.3) fails have vanishing conformal modulus. Then (4.2) can be obtained by following the standard argument for modulus of curve families (see Theorem 32.3 in [36] or Theorem II.2.4 in [26]).

We need the following estimates.

**4.4 Proposition** Let $f$ be a homeomorphism from $(R^3/Wh) \times R^m$ onto $R^{3+m}$. Then for each $k \geq 0$ and each $\Gamma \subseteq S_k$, the $(1+m)$–dimensional Hausdorff measures in $((R^3/Wh) \times R^m, \delta_a)$ and $R^{3+m}$ satisfy

1. $\mathcal{H}^{1+m}_{\delta_a}(\Gamma) \simeq a^k$,
2. $\mathcal{H}^{1+m}(f(\Gamma)) \geq C(f)2^k$

for some positive constant $C(f)$.

**4.5 Proposition** Let $f$ be a homeomorphism from $(R^3/Wh) \times R^m$ onto $R^{3+m}$. Then for each $k \geq 0$, the conformal moduli of surface families satisfy

1. $\text{Mod}(3+m)/(1+m)S_k \simeq (a^k)^{2m/(1+m)}$,
2. $\text{Mod}(3+m)/(1+m)f(S_k) \leq C(f)(2^{-k})^{3+m}/(1+m)$

for some positive constant $C(f)$.
5 Proof of Theorem 1.1

Theorem 1.1 follows from Theorem 3.8. The last sentence of Theorem 3.8, the only statement yet to be proved, follows from Proposition 4.1 and Proposition 4.5. The proof of Proposition 4.5 is given first assuming the validity of Proposition 4.4. The proof of Proposition 4.4 is given next assuming the validity of an estimate (5.1) on the intersection numbers. The proof of (5.1) shall occupy the remaining sections.

Proof of Proposition 4.5 Assume the validity of Proposition 4.4. Fix $k \geq 0$ and let $\rho$ be a nonnegative Borel function on $\mathbb{R}^3/Wh \times \mathbb{R}^m$ admissible for the surface family $S_k$, thus
\[
\int_{\Gamma} \rho d\mathcal{H}_{\delta}^{1+m} \geq 1
\]
for every $\Gamma \in S_k$. Therefore
\[
\int_{\tilde{U}_k \times [0,1]^m} \rho d\mathcal{H}_{\delta}^{3+m}
\]
\[
\simeq \int_{S^1 \times A} \left( \int_{[0,1]^m} \rho(\pi \phi^{(k)}(s, x), z) d\mathcal{H}^m(z) \right) a^{3k} d\mathcal{H}^3(s, x)
\]
\[
\simeq \int_A \left( \int_{\pi \phi^{(k)}(S^1 \times \{x\})} \left( \int_{[0,1]^m} \rho(\xi, z) d\mathcal{H}^m(z) \right) d\mathcal{H}^1_{\delta a}(\xi) \right) a^{2k} d\mathcal{H}^2(x)
\]
\[
\simeq \int_A \left( \int_{\pi \phi^{(k)}(S^1 \times \{x\}) \times [0,1]^m} \rho(\xi, z) d\mathcal{H}^{1+m}_{\delta a}(\xi, z) \right) a^{2k} d\mathcal{H}^2(x) \gtrsim a^{2k}.
\]
On the other hand,
\[
\int_{\tilde{U}_k \times [0,1]^m} \rho d\mathcal{H}_{\delta}^{3+m}
\]
\[
\leq \left( \int_{\tilde{U}_k \times [0,1]^m} \rho^{(3+m)/(1+m)} d\mathcal{H}_{\delta}^{3+m} \right)^{(1+m)/(3+m)} \left( \mathcal{H}_{\delta a}^{3+m}(\tilde{U}_k \times [0,1]^m) \right)^{2/(3+m)}
\]
\[
\leq C \left( \int_{\tilde{U}_k \times [0,1]^m} \rho^{(3+m)/(1+m)} d\mathcal{H}_{\delta}^{3+m} \right)^{(1+m)/(3+m)} a^{6k/(3+m)}.
\]
This implies
\[
\int_{\tilde{U}_k \times [0,1]^m} \rho^{(3+m)/(1+m)} d\mathcal{H}_{\delta}^{3+m} \gtrsim (a^k)^{2m/(1+m)}.
\]
Now set $\rho_0 = a^{-k}$ in $\tilde{U}_k \times [0,1]^m$ and $\rho = 0$ outside $\tilde{U}_k \times [0,1]^m$. Note from Proposition 4.4(1) that $C\rho_0$ is admissible for the surface family $S_k$ for some constant $C > 0$. 

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Assume that (5.1) is valid for the moment. Given we estimate the number

\[ N(\Gamma, j) \geq C(f)2^k \]

for all \( k > k_0, \Gamma \in S_k \) and \( j \in J \),

for some positive integer \( k_0 \) and some positive constant \( C(f) \) depending on \( f \).

Assume that (5.1) is valid for the moment. Given \( k > k_0 \) and a surface \( \Gamma \) in \( S_k \), let \( \zeta \) be the projection map from \( (\bigcup_{j \in J} D_j) \cap (\chi \circ f(\Gamma)) \) to \( J \) defined by

\[ \zeta(x) = j \text{ if } x \in D_j \cap (\chi \circ f(\Gamma)). \]

So \( \zeta \) is 1–Lipschitz. It follows from (5.1) and a coarse estimate (see Federer [13, Theorem 2.10.25]) that

\[ \mathcal{H}^{1+m}(\chi \circ f(\Gamma)) \geq \int_{J} N(k, \Gamma, j)\,d\mathcal{H}^{1+m}(j) \geq C(f)\mathcal{H}^{1+m}(J)2^k. \]

Since \( \chi \) is bi-Lipschitz, part (2) has been proved assuming (5.1).

Proof of Proposition 4.4 Part (1) follows immediately from the definition of the metric \( \delta_a \).

Part (2) can be proved by constructing a bi-Lipschitz homeomorphism \( \chi \) of \( \mathbb{R}^{3+m} \) with some specific properties, and then slicing surfaces in the collection \( \bigcup_{k=k_0}^{\infty} (\chi \circ f(S_k)) \) by a certain stack of standard 2–simplices \( \{D_j\} \) in \( \mathbb{R}^{3+m} \) with the parameter \( j \) ranging over an \((1+m)\)-dimensional cube \( J \) in \( \mathbb{R}^{3+m} \) orthogonal to the simplices \( \{D_j\} \). Finally, we estimate the number \( N(k, \Gamma, j) \) of points in the intersection \( D_j \cap (\chi \circ f(\Gamma)) \) from below by

\[ N(k, \Gamma, j) \geq C(f)2^j \]

for all \( k > k_0, \Gamma \in S_k \) and \( j \in J \),

for some positive constant \( C(f) \) depending on \( f \).

Therefore

\[ \text{Mod}(3+m)/(1+m)S_k \simeq (a^k)^2m/(1+m). \]

Hence

\[ \text{Mod}(3+m)/(1+m)f(S_k) \leq C(f)(2^{-k}(3+m)/(1+m)). \]

This completes the proof. \( \square \)
To complete the proof of Theorem 1.1, it remains to establish (5.1). In Section 6 we define \( \chi \) and locate the stack of two-simplices used for slicing, and in Section 8 we prove the lower estimate (5.1).

6 A stack of two-simplices

Denote by \( B_d(x, r) \) the closed ball having center \( x \) and radius \( r \) in the metric space \((X, d)\). We omit the subscript when the metric is Euclidean.

Let \( 0 \) be the origin of \( \mathbb{R}^m \) and \( Q \) be the point \((q, 0)\) in \((\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m\). Recall from (3.5), (3.6) and (3.7) that \( q \in \tilde{T}_k \subset \tilde{T}_k \cup \tilde{V}_k \subset B_{d_0}(q, C_0 a^k) \subset \mathbb{R}^3/\text{Wh} \) and that

\[
Q \in (\tilde{T}_k \cup \tilde{V}_k) \times [-a^k, a^k]^m \subset B_{\delta_d}(Q, C_1 a^k),
\]

for some constants \( C, C_1 > 1 \). Set

\[
v_k = \text{diam} \, f(B_{\delta_d}(Q, C_1 a^k));
\]

choose and fix an integer \( k_0 \geq 2 \) so that

\[
(6.1) \quad B(f(Q), 3v_{k_0}) \subset f(\tilde{T}_1 \times \mathbb{R}^m).
\]

The 2–simplices shall be chosen to lie in \( B(f(Q), 3v_{k_0}) \).

Set

\[
\alpha = \pi \phi^{(k_0)}(\partial B_0^2) \times \{0\},
\]

a meridian of \( \tilde{T}_{k_0} \times \{0\} \), where \( B_0^2 \) is the planar disk in \( \mathbb{R}^3 \) defined in the beginning of Section 2. Let

\[
(6.2) \quad \mathcal{A} = \left\{ x \in \mathbb{R}^3/\text{Wh} : \text{dist}_{d_0}(x, 0, \alpha) < \frac{c_0 a^{k_0}}{30} \right\} \times \left( -\frac{c_0 a^{k_0}}{30}, \frac{c_0 a^{k_0}}{30} \right)^m
\]

be a tubular neighborhood of \( \alpha \) not intersecting \( \tilde{T}_{k_0} \times \mathbb{R}^m \), where \( c_0 \) is the constant chosen in Section 3.

Let \( c_1 = \text{dist}(f(\alpha), f(\partial \mathcal{A}))/10 \). It follows from a PL–approximation theorem of Moise (Theorem 9.2 in the Appendix) that there exists an embedding \( \theta : \alpha \hookrightarrow \mathbb{R}^{3+m} \) such that \( l \equiv \theta(\alpha) \) is a piecewise linear topological 1–sphere in \( f(\mathcal{A}) \), and

\[
d(f(x), \theta(x)) < c_1 \quad \text{for all } x \in \alpha.
\]

The embedding \( \theta \) used for defining \( l \) shall play no role in the future. We observe that \( l \) and \( f(\alpha) \) are homotopic in \( f(\mathcal{A}) \) and that

\[
(6.3) \quad l \subset f(\mathcal{A}) \subset f((\tilde{T}_{k_0} \cup \tilde{V}_{k_0}) \times [-a^{k_0}, a^{k_0}]^m)
\]

\[
\subset f(B_{\delta_d}(Q, C_1 a^{k_0})) \subset B(f(Q), v_{k_0}).
\]
Here, as well as in the future, two curves $\beta$ and $\beta'$ are said to be homotopic in $X$ (or $\beta$ is homotopic to $\beta'$ in $X$) if the continuous maps defining the curves are homotopic in the target space $X$.

Since $3 + m \geq 4$, the PL $1$–sphere $l$ is unknotted in $\mathbb{R}^{3+m}$ and there is a global bi-Lipschitz homeomorphism $\chi$ of $\mathbb{R}^{3+m}$ that maps $l$ to the boundary of a standard $2$–simplex $D'$ contained in $B(Y, 2 \text{diam } l)$, $\chi(l) = \partial D'$, while fixes all points outside $B(Y, 2 \text{diam } l)$ for some point $Y \in l$. (See Theorem 9.4 in the Appendix.) Note from (6.3) that

\[ \chi = \text{id in } \mathbb{R}^{3+m} \setminus B(f(Q), 3v_{k_0}). \]

Choose and fix a $(1+m)$–dimensional cube $J$ in $\mathbb{R}^{3+m}$ which is orthogonal to the $2$–simplex $D'$ and is small enough such that all translates $j + \partial D'$ ($j \in J$) are contained in $\chi \circ f(\mathbb{A})$ and are homotopic to $\chi \circ f(\alpha)$ in $\chi \circ f(\mathbb{A})$. The translated standard $2$–simplices $D_j \equiv j + D'$, $j \in J$ enclosed by $j + \partial D'$ shall be used for slicing surfaces in the collection $\bigcup_{k=k_0}^{\infty} (\chi \circ f(S_k))$.

Since $\partial D_j = j + \partial D' \subset \chi \circ f(\mathbb{A}) \subset \chi(B(f(Q), v_{k_0})) \subset B(f(Q), 3v_{k_0})$, it follows that

\[ D_j \subset B(f(Q), 3v_{k_0}). \]

From (6.1) and (6.4), it follows that

\[ f^{-1} \chi^{-1}(D_j) \subset \tilde{T}_1 \times \mathbb{R}^m, \text{ for all } j \in J. \]

Since $f^{-1} \chi^{-1}(\partial D_j)$ and $\alpha$ are homotopic in $\mathbb{A}$, $\alpha$ is a meridian of $\tilde{T}_{k_0} \times \{0\}$ and $\mathbb{A} \cap \mathcal{L} = \emptyset$, the curve $f^{-1} \chi^{-1}(\partial D_j)$ is not contractible in $(\tilde{T}_0 \times \mathbb{R}^m) \setminus \mathcal{L}$ by Proposition 2.1. Therefore

\[ f^{-1} \chi^{-1}(D_j) \cap \mathcal{L} \neq \emptyset, \text{ for all } j \in J. \]

**6.5 Remark** For simplicity and with a slight abuse of notation, we continue to use the notation $f$ for the composition map $\chi \circ f$. Under this convention, for every $j \in J$,

\[ \partial D_j \subset f(\mathbb{A}); \]

$f^{-1}(\partial D_j)$ and $\alpha$ are homotopic in $\mathbb{A}$; and

\[ f^{-1}(D_j) \cap \mathcal{L} \neq \emptyset, \text{ } D_j \cap f(\mathcal{L}) \neq \emptyset \text{ and } f^{-1}(D_j) \subset \tilde{T}_1 \times [-C_2, C_2]^m \]

for some $C_2 > 1$. 

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7 Interior-essential components

The tori $T_k$ ($k \geq 0$) used in the Whitehead construction can be arranged topologically so that the meridian $\partial B_0^2$ on $\partial T_0$ bounds a 2–cell in $T_0$ which intersects every $T_k$ ($k \geq 1$) in $2^k$ mutually disjoint 2–cells enclosed by meridians of $T_k$. The lower estimate (5.1) is suggested by this idealized setting followed by a homological argument of Freedman and Skora [14]. In this section, we prove a version of their Lemma 2.5 for mappings instead of embeddings.

We adopt some statements from [9, pages 73–74] in locating the essential part of a continuous image of a 2–cell inside an $n$–manifold. Let $M$ be an $n$–manifold with boundary and $\omega$ a 2–manifold with boundary. A map $\Phi: (\omega, \partial) \to (M, \partial)$, meaning $\Phi(\omega) \subset M$ and $\Phi(\partial \omega) \subset \partial M$, is said to be interior-inessential if there exists a map $\Phi': \omega \to \partial M$ satisfying $\Phi'|\partial \omega = \Phi|\partial \omega$; it is said to be interior-essential if no such $\Phi'$ exists. In case $\omega$ is a closed 2–cell, $\Phi$ is interior-essential if and only if $\Phi(\partial \omega)$ is homotopically nontrivial in $\partial M$, but trivial in $M$.

Suppose that $\omega$ is a compact, connected 2–manifold in a 2–cell $D$. Denote by $D_\omega$ the unique 2–cell in $D$ containing $\omega$ with $\partial D_\omega \subset \partial \omega$. A map $\Phi: (\omega, \partial) \to (M, \partial)$ is said to be virtually interior-essential if $\Phi$ extends to an interior-essential $\Phi''$: $\partial_\omega \to M$ satisfying $\Phi''(\partial_\omega \setminus \omega) \subset \partial M$.

In case $M$ is a solid torus $T = S^1 \times B^2$, an interior-essential map $\Phi: (\omega, \partial) \to (T, \partial)$ necessarily maps one of the boundary components of $\omega$ to a homotopically nontrivial loop on $\partial T$. A map $\Phi: (\omega, \partial) \to (T, \partial)$ is virtually interior-essential if and only if $\Phi$ maps the outermost component of $\partial \omega$ to a nonzero multiple of a meridian on $\partial T$ while mapping all other components of $\partial \omega$ to trivial loops there. In other words $\Phi$, in fact the extension $\Phi''|D_\omega$, represents a nonzero multiple of a generator of the relative homology group $H_2(T, \partial; \mathbb{Z}) \equiv \mathbb{Z}$. Since a meridian and a core of a torus are linked, $\Phi(\omega)$ must intersect every core of the torus $T$.

Here and later, a closed curve on $\partial T$ is said to be a multiple of a meridian if it is homotopic, in $\partial T$, to $n$ times a meridian of $T$ for some integer $n$. A boundary component of a compact 2–manifold $\omega$ in a 2–cell $D$ is said to be outermost if it is not contained in the 2–cell in $D$ enclosed by any other component of $\partial \omega$.

Recall that the relative homology group

$$H_2(S^1 \times B^2, \partial; \mathbb{Z}) \equiv \mathbb{Z}$$

is generated by the equivalence class $[g]$ with $g: (\Delta, \partial \Delta) \to (S^1 \times B^2, \partial (S^1 \times B^2))$ being continuous and of degree $\pm 1$ on $\partial \Delta$, where $\Delta$ is a standard 2–simplex.

The following observation on meridians and longitudes is needed.

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7.1 Lemma  Let $T_k$ ($k \geq 0$) be the solid tori in the Whitehead construction. Then the meridians of $T_k$ are not contractible in $S^3 \setminus \text{Int}(T_k)$ hence not in $T_0 \setminus \text{Int}(T_k)$, and the longitudes of $T_k$ are not contractible in $T_0 \setminus \text{Int}(T_k)$.

Proof  The noncontractibility of the meridians follows from the fact that a meridian (resp. a longitude) of the torus $T$ is a longitude (resp. a meridian) of the torus $S^3 \setminus \text{Int}(T)$.

Since a core of $T_k$ and a core of $S^3 \setminus \text{Int}(T_k)$ form a Whitehead link for $k \geq 1$, there is a homeomorphism $h$ of $S^3$ interchanging these two cores [21, page 83]. In fact, $h$ can be chosen to map $T_k$ and $S^3 \setminus \text{Int}(T_k)$ onto $S^3 \setminus \text{Int}(T_{k-1})$ and $T_k$ respectively, thus to map $T_{k-1}$ onto $S^3 \setminus \text{Int}(T_k)$. This implies that $S^3 \setminus \text{Int}(T_k)$ is embedded in $S^3 \setminus \text{Int}(T_k)$ in same way that $T_k$ is embedded in $T_{k-1}$ for all $k \geq 1$. From this and the fact mentioned in the last paragraph, the statement on the noncontractibility of the longitudes follows. □

We now prove an analogue of Lemma 2.5 in Freedman and Skora [14] for mappings; it was proved there for embeddings and for the Bing double.

7.2 Lemma  Let $T_0$ and $T_1$ be the first two tori in the Whitehead construction, $\omega$ be a compact, connected 2–manifold in a 2–cell $D$, and $\Phi: (\omega, \partial) \to (T_0, \partial)$ be a virtually interior-essential map. Suppose that $\Phi(\omega)$ meets $\partial T_0 \cup \partial T_1$ transversally. Then $\Phi^{-1}(T_1)$ contains at least two components $\omega_1, \omega_2$ on which the maps $\Phi|\omega_i: \omega_i \to T_1$ ($i = 1, 2$) are virtually interior-essential.

Proof  Assume that $\Phi$ has been extended to the 2–cell $D_\omega$, which maps $\partial D_\omega$ to a nonzero multiple of a meridian of $T_0$ and maps $D_\omega \setminus \omega$ into $\partial T_0$.

We first check that $[\Phi|\Phi^{-1}(T_1), \partial] = 0$ in $H_2(T_1, \partial; \mathbb{Z})$, an analogue of an assertion of Freedman and Skora about the Bing double [14, page 82]. Choose a smooth embedding $g: (\Delta, \partial \Delta, \Delta \setminus \partial \Delta) \hookrightarrow (T_0, \partial T_0, T_0 \setminus \partial T_0)$ in such a way that $g(\Delta)$ meets $\partial T_1$ transversally, $g^{-1}(T_1)$ consists of exactly two 2–cells $\Delta_i$ ($i = 1, 2$), $[g|\partial] \subset H_2(T_0, \partial; \mathbb{Z})$, and $g|\Delta_1$ and $g|\Delta_2$ represent generators of $H_2(T_1, \partial; \mathbb{Z})$ of opposite signs. Hence

$$[g|\Delta_1, \partial] + [g|\Delta_2, \partial] = 0 \text{ in } H_2(T_1, \partial; \mathbb{Z}).$$

Identify the 2–cells $D_\omega, \Delta_1$ and $\Delta_2$ with the standard 2–simplex $\Delta$ with proper orientations. Since

$$[\Phi, \partial] = \pm n[g, \partial] \text{ in } H_2(T_0, \partial; \mathbb{Z}),$$

(7.3) $\Phi \equiv n \cdot g + \tau = \partial \sigma,$
We shall alter the assumption that the minimal 2–cell $D_{\omega'}$ in $D_\omega$ containing $\omega'$ ($\omega' \in \Omega$) are nested and contain $\omega^1$ in their intersection. In other words, the elements of $\Omega$, $\omega^1, \omega^2, \ldots, \omega^N$, can be ordered so that $\omega^1 = D_{\omega^1} \subset D_{\omega^2} \subset \cdots \subset D_{\omega^N} \subset D_\omega$.

We shall alter $\Phi$ in such a way, while not changing the homology class $[\Phi|\Phi^{-1}(T_1), \partial]\in H_2(T_1, \partial; \Z)$, that $\Phi^{-1}(T_1)$ has only one interior-essential component, namely $D_{\omega^N}$. Since $\Phi(\partial D_{\omega^N})$ is noncontractible in $T_0 \setminus \text{Int}(T_1)$, $\Phi(\partial D_{\omega^N})$ must be homotopically nontrivial in $\partial T_1$. It follows then $[\Phi|\Phi^{-1}(T_1), \partial] = [\Phi|\partial D_{\omega^N}, \partial] \neq 0$.
The boundary of $\omega^2$ consists of an outermost component $\partial D_{\omega^2}$ and a special component $b$ that encloses a 2–cell $D_b$ in $D_\omega$ which contains $\omega^1$ in its interior, and possibly some other components $\beta$’s whose interiors contain no elements of $\Omega$. Since $D_\beta$ does not contain any element of $\Omega$, $\Phi(\beta)$ is trivial in $\partial T_1$. After altering $\Phi$ in the interior of each $D_\beta$, we may assume that $\bigcup_\beta \Phi(D_\beta) \subset \partial T_1$ and that $\Phi$ maps the annular region in $D_\omega$ bounded by $b$ and $\partial D_{\omega^2}$ into $T_1$. The 2–cell $D_b$ consists of $D_{\omega^1}$ and an annular region $A$ in $D_\omega$ bounded by $\partial D_{\omega^1}$ and $b$. The annulus $A$ contains no elements of $\Omega$ due to the ordering. Modifications can be made on the interior-inessential components in $A$, so that $\Phi|A$ maps $A$ into $T_0 \setminus \text{Int}(T_1)$. The annulus $A$ provides a homotopy between $\Phi|b$ and $\Phi|\partial D_{\omega^1}$ in $T_0 \setminus \text{Int}(T_1)$. By homotopy invariance, both $\Phi(b)$ and $\Phi(\partial D_{\omega^1})$ are $n_1$ times a meridian of $T_1$. So $\Phi$ can again be altered in $A \setminus \Phi^{-1}(T_1)$ such that $\Phi(A) \subset \partial T_1$. After these changes, $D_{\omega^2}$ becomes a component of $\Phi^{-1}(T_1)$ while the homological relation $[\Phi|\omega^1, \partial] + [\Phi|\omega^2, \partial] = [\Phi|D_{\omega^2}, \partial]$ remains.

Continuing inductively if $N > 2$, $\Phi$ can be altered so that $D_{\omega^N}$ becomes the only interior-essential component of $\Phi^{-1}(T_1)$.

As noted earlier $[\Phi|\Phi^{-1}(T_1), \partial] = [\Phi|D_{\omega^N}, \partial]$ is trivial in $T_1$, which gives the desired contradiction. This completes the proof of the lemma.

8 A lower estimate on the intersection numbers

In this section, we apply Lemma 7.2 to obtain the estimate (5.1).

8.1 PL–approximation

Fix a parameter $j \in J$; write $D$ for the simplex $D_j$ used for slicing, and

$$F = f^{-1} \mid D.$$ 

Let $\Pi: (\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^n \to \mathbb{R}^3/\text{Wh}$ be the projection map

$$\Pi(x, z) = x.$$ 

The goal of this subsection is to construct a single-valued version of $\pi^{-1} \Pi F|D: D \to \mathbb{R}^3$ whose image intersects the boundaries of the tori transversally.

For the purpose of applying a PL–approximation (Theorem 9.5 in the Appendix), the manifold $(\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^n$ is equipped with a PL–structure and a metric, induced from $\mathbb{R}^{3+n}$ by a fixed homeomorphism (unrelated to $f$) $h: (\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^n \to \mathbb{R}^{3+n}$,
which is $\pi^{-1} \times \text{id}$ outside $\tilde{T}_{K+1} \times \mathbb{R}^m$ and is diffeomorphic off $\mathcal{L}$. Fix a large integer $K > k_0$ and let

\begin{equation}
\epsilon = c_0 a^{K+2}/30.
\end{equation}

From Theorem 9.5 it follows that for any $\epsilon' > 0$, $F|D$ can be $\epsilon'$--approximated by a locally flat PL embedding $L: D \hookrightarrow (\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m$. When $\epsilon'$ is sufficiently small, the approximation satisfies

\begin{equation}
d_{\partial a}(F(x), L(x)) < \epsilon, \quad \text{for all } x \in D \setminus f(\tilde{T}_{K+1} \times \mathbb{R}^m),
\end{equation}

with respect to the original metric. Adjusting $L$ to one in general position with respect to the boundaries of the tori, we may assume that $L(D)$ and $(\partial \tilde{T}_{k_0} \cup \bigcup_{k=k_0}^{K} \partial \tilde{T}_{k+1}) \times \mathbb{R}^m$ meet transversally and their intersection is an 1--manifold having no boundary. Adjusting $L$ again, we may further assume that the projection $\Pi$ embeds each simplex in $L(D) \setminus (\tilde{T}_{K+1} \times \mathbb{R}^m)$, that $\Pi L(D)$ and $\partial \tilde{T}_{k_0} \cup \bigcup_{k=k_0}^{K} \partial \tilde{T}_{k+1}$ meet transversally and that $(\Pi L)^{-1}(\partial \tilde{T}_{k_0} \cup \bigcup_{k=k_0}^{K} \partial \tilde{T}_{k+1})$ is a 1--manifold in $D$ having no boundary. See Rourke and Sanderson [27, Chapter 5], Rushing [28, page 33] and Theorem 9.6 in the Appendix.

Note from (6.2), (6.6), (8.2) and (8.3) that $L(\partial D)$ is homotopic to the meridian $\alpha$ of $\tilde{T}_{k_0} \times \{0\}$ in $\tilde{V}_{k_0} \times \mathbb{R}^m$. By Proposition 2.1,

\begin{equation}
L(\partial D) = \partial L(D) \text{ is not contractible in } (\tilde{T}_0 \times \mathbb{R}^m) \setminus \mathcal{L};
\end{equation}

and by (6.7), (8.2) and (8.3),

\begin{equation}
q \in \Pi L(D), \quad L(D) \cap \mathcal{L} \neq \emptyset \quad \text{and} \quad L(D) \subseteq (\tilde{T}_1 \cup \tilde{V}_1) \times [-C_2 - 1, C_2 + 1]^m.
\end{equation}

The function $\pi^{-1} \Pi L$ is not single-valued on the set $L^{-1}(\mathcal{L}) \cap D$; we modify $\pi^{-1} \Pi L$ near $L^{-1}(\mathcal{L})$ as follows. Let $\Lambda_1, \Lambda_2, \ldots, \Lambda_N$ be the 2--cells in $D$ enclosed by the outermost components of $L^{-1}(\partial(\tilde{T}_{K} \times \mathbb{R}^m))$. Then the 2--cells $\Lambda_1, \Lambda_2, \ldots, \Lambda_N$ are mutually disjoint,

\[ L^{-1}(\mathcal{L}) \subseteq \bigcup_{i=1}^{N} \Lambda_n, \quad \text{and} \quad L \left( D \setminus \bigcup_{i=1}^{N} \Lambda_n \right) \cap (\tilde{T}_{K} \times \mathbb{R}^m) = \emptyset. \]

Note however $L(\bigcup_{i=1}^{N} \Lambda_n)$ need not be contained in $\tilde{T}_{K} \times \mathbb{R}^m$. Since the homeomorphism $h: (\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m \to \mathbb{R}^{3+m}$ providing the PL--structure on $(\mathbb{R}^3/\text{Wh}) \times \mathbb{R}^m$ is $\pi^{-1} \times \text{id}$ outside $\tilde{T}_{K+1} \times \mathbb{R}^m$, the function $\Phi: D' \to \mathbb{R}^3$ defined by

\[ \Phi = \begin{cases} 
\pi^{-1} \Pi L & \text{in } D \setminus \bigcup_{i=1}^{N} \Lambda_n, \\
\Pi' h L & \text{in } \bigcup_{i=1}^{N} \Lambda_n.
\end{cases} \]
is continuous on $D$. Here $\Pi' \colon \mathbb{R}^3 \times \mathbb{R}^m \to \mathbb{R}^3$ is the projection with $\Pi'(x, z) = x$.

From the discussion leading to (8.4) and (8.5), it follows that

$$\Phi(\partial D) = \pi^{-1} \Pi L(\partial D) \subset V_{k_0} \quad \text{and} \quad \Phi(D) \subset T_1 \cup V_1 \subset T_0.$$

$\Phi(\partial D)$ is not contractible in $T_0 \setminus Wh$.

(8.6) \quad $\Phi(D) \cap t_{k_0} \neq \emptyset$ and $\Phi(D) \cap T_k \neq \emptyset$ for all $k \geq k_0 + 1$.

Define also a single-valued version of $\pi^{-1} \Pi F$

$$\Psi = \begin{cases} \pi^{-1} \Pi F & \text{in } D \setminus \bigcup_1^N \Lambda_n, \\ \Pi'h F & \text{in } \bigcup_1^N \Lambda_n. \end{cases}$$

The $\epsilon$–closeness (8.3) of $F$ and $L$ implies that $\Psi|(D \setminus \cup_1^N \Lambda_n)$ and $\Phi|(D \setminus \cup_1^N \Lambda_n)$ are $\epsilon$–close with respect to the metric $d_a$ on $\mathbb{R}^3 \setminus Wh$.

### 8.7 Intersection

We now apply Lemma 7.2 to torus pairs $(t_{k_0}, T_{k_0+1})$, $(T_{k_0+1}, T_{k_0+2}), \ldots, (T_{K-1}, T_K)$. Notice that given any such pair, there is a homeomorphism of $S^3$ that maps the first torus in the pair onto $T_0$ and the second one onto $T_1$.

To begin, let $\omega_{k_0}$ be an innermost component of $\Phi^{-1}(t_{k_0})$ on which $\Phi$ is interior-essential. By (8.6), $\omega_{k_0}$ must exist and is nonempty. Following the argument in Lemma 7.2 for the statement that $\Phi|\omega^1$ is virtually interior-essential, we may conclude that $\Phi \colon (\omega_{k_0}, \partial) \to (t_{k_0}, \partial)$ is virtually interior-essential; here the fact that neither a meridian of $t_{k_0}$ nor a longitude of $t_{k_0}$ is contractible in $T_0 \setminus \text{Int}(t_{k_0})$ is needed.

Applying Lemma 7.2 to the torus pair $(t_{k_0}, T_{k_0+1})$, we conclude $\Phi^{-1}(T_{k_0+1})$ contains at least two components $\omega^{1}_{k_0+1}$ and $\omega^2_{k_0+1}$ on which the maps $\Phi|\omega^1_{k_0+1} : \omega^1_{k_0+1} \to T_{k_0+1}$ ($i = 1, 2$) are virtually interior-essential. Apply Lemma 7.2 again to each $\omega^i_{k_0+1}$ ($i = 1, 2$) to obtain at least four components $\omega^i_{k_0+2}$ ($1 \leq i \leq 4$) of $\Phi^{-1}(T_{k_0+2})$ on which the maps $\Phi|\omega^1_{k_0+2} : \omega^1_{k_0+2} \to T_{k_0+2}$ ($1 \leq i \leq 4$) are virtually interior-essential. Continuing inductively, we get for each $k$, $k_0 + 1 \leq k \leq K-1$, at least $2k-k_0$ components $\omega^i_k$ ($1 \leq i \leq 2k-k_0$) of $\Phi^{-1}(T_k)$ on which $\Phi$ is virtually interior-essential. In fact, the proof of Lemma 7.2 also shows that for a fixed $k$, the minimal 2–cells $D_{\omega^i_k}$ in $D$ containing $\omega^i_k$ ($1 \leq i \leq 2k-k_0$) are mutually disjoint, and that each $\Phi(\partial D_{\omega^i_k})$ is a nonzero multiple of a meridian of $T_k$.

Fix an $\omega^i_k$ with $k_0 + 1 \leq k \leq K-1$ and $1 \leq i \leq 2k-k_0$. For any $\gamma$ in the curve family $C_k$ defined in Section 4, $\pi^{-1}\gamma$ (a core of $T_k$) and $\Phi(\partial D_{\omega^i_k})$ are linked. So $\pi^{-1}\gamma$ intersects $\Phi(D_{\omega^i_k})$, in fact intersects $\Phi(\omega^i_k)$. 

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For each $\gamma \in C_k$, the core $\pi^{-1}\gamma$ intersects $\Psi(\omega^i_k)$ also. This can be seen as follows. Since $\pi^{-1}\gamma \subset U_k \subset t_k$ and $\Phi(\partial D_{\omega^i_k}) = \pi^{-1}\Pi L(\partial D_{\omega^i_k}) \subset \partial T_k$, we have

$$30\epsilon = c_0d^{K+2} \leq \text{dist}_{d_a}(t_k, \partial T_k) \leq \text{dist}_{d_a}(\pi^{-1}\gamma, \Phi(\partial D_{\omega^i_k})).$$

From the $\epsilon$–closeness of $\Psi$ and $\Phi$, it follows that $\Psi(\omega^i_k)$ is contained in $V_k \cup T_k$, a neighborhood of $T_k$, and that $\Psi|\partial \omega^i_k$ and $\Phi|\partial \omega^i_k$ are homotopic in $V_k \setminus U_k$, a neighborhood of $\partial T_k$ outside $t_k$. So $\pi^{-1}\gamma$ and $\Psi(\partial D_{\omega^i_k})$ are also linked. Therefore $\pi^{-1}\gamma$ intersects $\Psi(\partial D_{\omega^i_k})$, in fact intersects $\Psi(\omega^i_k)$.

The intersection of $\pi^{-1}\gamma$ and $\Psi(\omega^i_k)$ necessarily takes place at points in $U_k$, which is outside the torus $T_K$. Therefore $\Psi = \pi^{-1}\Pi F$ at the points of intersection. So $\gamma$ intersects $\Pi F(\omega^i_k)$ for each $\gamma \in C_k$. Consequently, $\Gamma$ intersects $F(\omega^i_k)$ for each $\Gamma \in S_k$.

This together with Remark 6.5 shows that for each $k$, $k_0 + 1 \leq k \leq K - 1$,

$$N(k, \Gamma, j) \geq 2^{k-k_0} \quad \text{for all } \Gamma \in S_k \text{ and } j \in J.$$

Since $K$ can be arbitrarily large, estimate (5.1) follows. This completes the proof of Theorem 1.1.

9 Appendix

We state some topological facts needed in our proof.

The first theorem is about the size of the complement of a non–simply connected set proved by Martio, Rickman and Väisälä [23].

9.1 Theorem Suppose that $G$ is a simply connected domain in $\mathbb{R}^n$ ($n \geq 3$) and $A$ is a closed subset of $G$. If $G \setminus A$ is not simply connected, then $A$ must have positive $(n-2)$–dimensional Hausdorff measure.

Next is a theorem about PL–approximation of embeddings of one-dimensional complexes due to Moise [25, page 46].

9.2 Theorem Let $K^1$ be a 1–dimensional complex, $f: |K^1| \hookrightarrow \mathbb{R}^2$ an embedding, and $\psi > 0$ a continuous function on $|K^1|$. Then there exists a piecewise linear embedding $\theta: |K^1| \hookrightarrow \mathbb{R}^2$ such that

1. $|\theta(x) - f(x)| < \psi(x)$ for all $x \in |K^1|$ ($\psi$–approximation of $f$),

2. $\theta(v) = f(v)$ for all vertices $v$ of $K^1$.
9.3 Remark The theorem remains true if the target space is $\mathbb{R}^n$ for any $n \geq 2$. The proof is essentially unchanged.

The following theorem on unknotting spheres is due to Zeeman [40]; the second sentence in the statement below can be deduced from the proof of Theorem 5.6 in Rourke and Sanderson [27] and the propositions mentioned therein.

9.4 Theorem Any piecewise linear topological 1–sphere $l \subset S^n$ is unknotted in $S^n$ when $n \geq 4$. More precisely, there is a global PL–homeomorphism $L$ of $S^n$ with the following properties:

1. $L$ maps $l$ onto the boundary of a standard 2–simplex, in $B(Y, 2 \text{diam } l)$ for some point $Y \in l$.
2. $L \equiv \text{id}$ in $S^n \setminus B(Y, 2 \text{diam } l)$.

The following PL–approximation of topological embeddings of $k$–cells into a manifold $M^n$ is due to Ancel and Cannon [2] when codimension is 1, due to Miller [24] and Černavskii [8] when codimension is 3 or higher and due to Venema [37; 38] when codimension is 2. We need it for $k = 2$ and $n \geq 4$.

9.5 Theorem Let $h: I^k \to M^n$ be a topological embedding of the closed $k$–cell $I^k$ into a piecewise linear $n$–manifold $M^n$ and $n-k \geq 1$. Then for every $\varepsilon > 0$ there exists a locally flat piecewise linear embedding $L: I^k \to M^n$ such that $d(h(x), L(x)) \leq \varepsilon$ for each $x \in I^k$.

The following theorem on transversality is well-known (see for example Daverman [9, page 69]). When the maps are piecewise linear the proof is simpler.

9.6 Theorem Suppose $M^n$ is an $n$–manifold, $\Sigma$ is an $(n-1)$–manifold embedded in $M$ as a closed and bicollared subset, $F: B^2 \to M$ is a continuous map, $U$ is an open subset of $M$ containing $\Sigma$, and $\varepsilon > 0$. Then there exists a map $L: B^2 \to M$ satisfying

1. $L|(B^2 - F^{-1}U) = F|(B^2 - F^{-1}U)$,
2. $d(L, F) < \varepsilon$,
3. $L^{-1}\Sigma$ is a 1–manifold in $B^2$ with $\partial(L^{-1}\Sigma) = \partial B^2 \cap L^{-1}\Sigma$,
4. for any point $x \in L^{-1}\Sigma$, $L(B^2)$ pierces $\Sigma$ at $L(x)$, i.e., for each neighborhood $W$ of $x$ in $B^2$, $L(W)$ touches both sides of the bicollar on $\Sigma$ near $L(x)$.

We say $L(B^2)$ and $\Sigma$ meet transversally if the map $L: B^2 \to M$ satisfies (3) and (4).
References


Quasisymmetric nonparametrization and the Whitehead continuum


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